A STUDY OF DIMENSIONAL LIMITATIONS IN LOW PRESSURE DIE CASTING

AUTHOR: David Farnsworth

B. App. Sci.(R.M.I.T.)

Thesis submitted as a requirement for the completion of a

Masters of Engineering Science Degree

University of Tasmania.

December 1997

AUTHORITY OF ACCESS FOR THESIS

This thesis is not to be made available for loan or copying until the permission of Comalco limited has been sought. Following that the Thesis may be made available for loan and limited copying in accordance with the Copyright Act 1968.

Signed David Forsworth Dated: 12/4/97

DECLARATION

This Thesis contains no material which has been previously accepted for a degree or diploma by the University or any other institution, except by way of background information and has been duly acknowledged in the Thesis. To the best of the authors knowledge and belief no material has been previously published or written by any other person except where due acknowledgment is made in the text of the Thesis.

Signed: David Forgwell ...... Dated: ....12/4/97.....................

ACKNOWLEDGEMENTS

This Thesis is in collaboration with Southern Aluminium and the University of Tasmania. In particular Dr. Vishy Karri from the University of Tasmania and David Sadler from Southern Aluminium Pty Ltd. I would like to give the highest possible praise to these two gentleman for their encouragement and support. In particular Dr. Vishi Karri whose constant guidance, support and much needed enthusiasm provided much of the motivation to keep work progressing. Thanks to David Sadler and his support both financial and moral, and the time required off my normal job. Special thanks go to my colleagues who provided much needed technical support/input, people such as Tony Hewitt, Tony Curtayne, Mark Kerrison and Gerd Siebert, who all contributed technically to the thesis. I would like to thank all personal at Southern Aluminium, since during the course of this thesis Southern Aluminium went through the process of selling the business, not selling the business, and eventually closure. Finally special thanks go to my wife and family who put up with my modes and time spent away from them. All my love to Pru, Ashleigh, and William Farnsworth.

ABSTRACT

This project is a study of low- pressure die casting process in Southern Aluminium Pty. Ltd., a subsidiary of Comalco in Tasmania. The first major stage in the wheel manufacturing process is casting. Wheels for automobile companies such as Nissan, Ford and Mazda are cast using a low-pressure die casting process. A casting cycle involves filling of the dies with molten aluminium solidifying the aluminium in the dies, ejecting the solidified castings from the dies, quenching the castings to a temperature close to room temperature and delivering the castings to the operator for further processing. When running at full capacity, each casting machine is capable of producing two castings simultaneously every six minutes. Each metal transfer into the caster crucible yields enough volume of metal for the production of approximately sixty wheels. The operator that initiates the casting cycle is responsible for some further wheel processing operations. These operations include the stamping of each cast wheel with a melt number stamp, manually removing any visible marks from the front face of each wheel and removing excess aluminium from the top and bottom rim of each wheel and finally, checking the castings for distortion using a distortion gauge.

Each time the caster crucible is filled, an alloy sample is taken from the crucible and examined spectrographically to determine alloy composition. The alloy composition is recorded and the melt number is changed. The melt number of each cast wheel can then be related to an exact alloy composition. A distortion gauge placed on the front face of the wheel will inform the operator of the wheel distortion. A wheel that it badly distorted, greater than plus or minus half a millimeter out of plane is rejected. Further there is limitations on the minimum thickness that can be cast on these wheels. The conditions to achieve the minimum thickness in effective casting have been established in industry over a series of investigations. This project highlights the conditions necessary to maintain minimum thickness in wheel castings, produced by low-pressure die casting, by taking into consideration various process variables. The stress analysis and solidification rates have been studied as a part of this investigation using finite element and finite difference methods. The experimental investigation in achieving minimum effective casting thickness complements the results from the finite element investigations. The experiments were carried out over

500 wheels for Nissan, Ford and Mazda wheels to understand the effect of process variables on cast dimensions This investigation gives a better understanding of the major process variables that control the thickness in casting process. The outcomes of this thesis are extremely useful for practicing engineers in achieving minimum effective thickness in aluminium wheel castings, using low pressure die casting, in modern manufacturing industry.

CONTENTS

Declaration i
Acknowledgments ii
Abstract iii

Chapter One: Introduction ***1***

Chapter Two: Literature Survey 17

2.1 Patterns and Moulds 18
2.2 Melting and Metal 24
2.3 Defects in Casting 27
2.4 Other Casting Processes 30
2.5 Casting Processes Specific to Wheels 36
2.6 Concluding Remarks 45

Chapter Three: Finite Element Modelling ***46***

3.1 Finite Element Methods 49
3.2 Solution Using PATRAN 56
3.3 Use of FEA (Stress Analysis at Southern Aluminium) 62
3.4 The use of MAGMA solidification 68
3.5 Concluding Remarks 78

Chapter Four: Flexible Manufacturing Casting Cell ***80***

4.1 The Operation Layout 91
4.2 The Low Pressure Fill 94
4.3 The Die Operation 96
4.4 Concluding Remarks 97

Chapter Five: Qualitative and Quantitative Verification of Casting Dimensions ***99***

5.1 Ability to Manufacture and Pass Stress Requirements 99
5.2 Concluding Remarks 108

Chapter Six: Final Concluding Remarks and Future Work ***109***

6.1 Proposed Future Work 112

References ***113***

CHAPTER 1

INTRODUCTION

Our current lifestyle and expectations is a result of the industrialised age, critical to this is manufacturing. Manufacturing is on of the key components to the maintenance and improvements to our lifestyle and expectations. This lifestyle is only possible because of advances in mankind's ability to produce useful products on an economic scale. Technologies enable the production of components to stringent controls; critical controls are function and costs. The future of manufacturing lies in the ability to meet these criteria at higher and higher levels. This is the basis of mans economic advancement. The advances in industrialised countries such as Australia can only occur if we provide support to the process of improving our technologies and as a result our lifestyle and economic security. This is a fundamental of capitalist societies until this type of society no longer remains predominant the pressure explained above will remain

Manufacturing is the basis of industrialised societies. The process of improved standard of living drives the process of improvement. A person's expectation (or standard of living) changes with time. In a dynamic economic society this expectation will continually rise. Examples of this are boundless, but in the automotive environment the pace of change is huge. 40 years ago oil filters were optional, 30 years ago heater were optional, 20 years ago automatics were the least common option, while10 years ago air bags where uncommon. Today a majority of the options of a few years ago are now standard. Production as a part of Manufacturing involves the process of converting raw materials into useful products.

It can also be described as a process, which together with other manufacturing processes like design produces a product. Each of the manufacturing processes involved either improves the value of a product or supports the activity of increasing the value of the product. The process of increasing the value is referred to as a value-added activity, the process of **not** supporting this activity can be determined as a non value-added activity. The bending of a piece of material is often referred to as a value added activity, the process of moving the material to the workstation (although a necessary activity) is referred to as a non-value added activity, since the component has no increase in value. One approach to the optimisation of manufacturing can be referred to as the minimisation of non-value added activities. Manufacturing changes the form of materials, using various processing techniques, to create useful products. The changes to material therefore produce a useful product of a higher value than prior to the beginning of the process. Raw materials needed for the production of any item has a value in its prime form. This is why manufacturing occurs, to increase value and hence produce an economic advantage.

If the enterprise adds value at a lower cost than the value it receives for its products it makes a profit. Profit is the amount of money resulting when revenues exceed costs, costs includes items such as depreciation, energy costs, and cost of raw materials, labour costs etc. Successful organisations will have increasing value-added activities and hence higher profits. It is the profit that allows the payment of dividends to owners and shareholders, the purchase of new equipment and plants and the payment of taxes.

A manufacturing system coordinates elements of input, process and output. Input in a manufacturing system includes consumer/customer demand, material, money, energy, human resources and education, whilst process includes design, production and management. A combination of input and process in a manufacturing system result in output of consumer goods, capital goods, satisfaction and quality and cost effectiveness.

Despite some advantages Australia has the difficulty of being a small player in economic manufacturing. Australia's economic basis involves dependence on primary industry ie mining and agricultural products. Australia relies on this wealth and does not strategically rely on manufacturing. The "Tiger" economies on the other hand rely on manufacturing. In 1990 only 16% of Australia's merchandise exports were manufactured products[1]. The manufacturing capability of Australia does not compare well by this measure whether it is compared with the Tiger economies in our region. Countries such as Korea and Taiwan have a manufacturing export rate of 90%. Canada, a country often compared with Australia has a manufacturing export rate of 58%. Economies with a low resource base must rely on manufacturing for their wealth. This can in some circumstance be considered an advantage. Therefore if Australia is to survive in the world competitive manufacturing environment in need to adopt innovative and world leading practices.

[1] World Competitiveness report (1992), IMD and EMF foundation, Cologny/Geneva, Switzerland

It should be noted that advances in manufacturing are often linked with advances in automation. Modern Australian manufacturing can and in some circumstances does compete well in the world but due to our relatively high labour rates Australia must compete from a level of higher technology and methodology. Automation can for example replace tedious competitive jobs or jobs that have adverse environments. The extra advantages of using automation in such roles is reduction in a faulty product due to the elimination of human errors and the consistent quality and rate of production regardless of whether it is Friday afternoon or Monday morning.

Automation is only one part of the manufacturing process operation hence other methods and processes must be considered. The common methodology used for all these processes include common processes such as Just in Time (JIT), Manufacturing requirements planning (MRP) and fail safe mechanisms. The results of these activities are to provide assistance with optimisation of all facets of manufacturing from inventory control to machine line layout and sequencing. These systems become a manufacturing philosophy with the intent of productivity optimisation by maximising efficiency of product flow and minimising inventory.

In all these optimisation systems there is a common goal of maximising productivity within all areas of the manufacturing environment with each area contributing in a cumulative manner to the operations overall productivity. Flexible manufacturing systems can contribute to productivity improvements in actual manufacturing operations. Materials requirement planning (MRP), on the other hand, provides assistance with efficiency improvements in materials requisitioning and inventory levels. Another very important factor in improving productivity in manufacturing operations is to be able to understand and optimise the product flow through the plant. The product flow analysis is called PFA.

Consumers/Customers demand more for less, this is the driver for continual improvement. If a manufacturing organisation is to exceed it must not to be left behind as other manufacturers meet those demands. For this reason, consumer demand is a driving force for improving technologies in modern manufacturing systems. Improvements in productivity can be described as lowering the Non Value added activities. This also extends to changes in these same operating cycles and processes to ensure a better quality product at the end of production. Ultimately, the objective of productivity improvements is to result in the production of more items with higher quality at a lower cost. This is the aim that modern manufacturing organisations endeavour to achieve. As a result of successful productivity improvements the output from manufacturing systems such as quality and cost effectiveness are achieved.

Planning of manufacturing activities is necessary for a manufacturing operation to be efficient. Process planning determines the required operations and necessary facilities to manufacture a part or product. It is concerned with selecting methods of production, tooling, fixtures and machinery, sequencing of operations and assembly. Two aspects of process planning are specification of a suitable production schedule and determining production speeds for minimum cost and maximum production rate. Process planning determines product flow within a manufacturing system. Product flow is the flow of product throughout the manufacturing system from initial to finished product. Factors that influence product flow are the sequencing of necessary production operations to give the most efficient process, plant layout and the ordering of operations such that necessary tasks are completed in the correct order of processing. Product flow analysis assists in achieving the most economical use of floor space and is used to assess sequencing of operations to determine the optimum arrangement of equipment. In its broadest sense, product flow is used to analyse products flowing through a plant and assess the most appropriate paths and sequencing of events. The study of product flow within a manufacturing environment involves the optimisation of a problem by analysis of all the options and alternatives within the problem. It is very important that the focus of the problem remains the desire for an increase in productivity. There is a need for understanding product flow and process planning as a part of controlling and optimising overall production time and production rate. Without efficient product flow productivity cannot be optimum. Improvements that arise from product flow analysis contribute to the productivity improvements of the operation.

Due to the increasing desire to improve productivity in manufacturing systems automation is becoming increasingly popular. Automation is the process of following a predetermined sequence of operations with little or no human labour, using specialised equipment and devices that perform and control manufacturing operations. This is achieved with various devices, sensors, actuators techniques and equipment that are capable of observing the manufacturing process, making decisions concerning the changes that should be made in the process and controlling all aspects of the processing operations. The major goals of automation in manufacturing facilities are to integrate various operations to improve productivity, increase product quality and uniformity, minimise cycle times and effort, reduce labour costs, reduce possibilities of human error and raise the level of safety for personnel. The basis areas of activity in manufacturing plants that are subject to automation include manufacturing processes such as machining, forging and grinding; material handling during various stages of completion; inspection of part for quality, dimensional accuracy and surface finish; assembly of parts and final product; and packaging.

Material handling and material movement is a significant aspect of automation in manufacturing plants. Most manufacturing systems require the moving of materials and parts between processes in order to produce a finished product. Manufacturing systems with individual operations, require a large amount of material handling for the transfer of parts between processes. Material handling between processes adds cost but not value to a product and for this reason should be kept as minimal as possible.

Flow of materials and components throughout the manufacturing cycle is greatly effected by plant layout. The arrangement of production machinery and material handling equipment should be orderly and efficient. Various factors need to be considered when choosing a material handling method for a particular manufacturing operation. These include shape, weight and characteristic of parts; types of movement and distances involved the position and orientation of parts during movement to their final destination. Other factors include condition of the path along which parts are to be transported; degree of automation and control desired and integration with other systems and equipment; operator skill required and economic condition.

This thesis will look at some of the common variables within the low-pressure casting process and determine some limiting process variables, specifically dimensional aspects on the design of the product. It can be demonstrated that the understanding of a process is critical to the process flow and that an unsuccessful introduction or production of the part will significantly damage the product flow and hence optimisation of production will not occur. It is hoped this thesis will lead to a higher understanding as to the limits that can be placed on the product. Alternatively if the product needs, for commercial reasons to exceed those limitations, clear directions and possibilities can be explored early in the design process.

The variables this thesis will look at are primarily weight related and hence will focus on dimensional minimums. Southern Aluminium is a wheel producer in the world market looking for competitive edge. One of those advantages is Southern Aluminium's ability to produce product at as light as weight as possible

It is generally excepted that heavier product is easier to manufacture. This sets up a potential conflict of interest between production requirements and customer requirements. It should be clear to all manufactures that two prime criteria must be reached these are:

1. The proposed product must fulfil the customer general requirements these include in order of priority safety, price, and weight.
2. Southern Aluminium must be able to manufacture the product in a profitable and effective manner.

The intent of this thesis is to clearly or provide a methodology to define the manufacturing possibilities in order that this can be used to smoothly inform customers as to the possibilities of their styling requirement.

There have been tremendous improvements in vehicle performance/function over recent years. Performance improvements relate primarily to features and fuel economy. Consumers of automobiles are unlikely to change their expectation for creature comforts, eg air conditioners, power steering, NVH (Noise Vibration Harshness), air bags etc. Due to these continuing pressures the emphasis will be losing weight without losing function. Every extra gram of weight adds significantly to the vehicles fuel usage over the life of the vehicle.

The other enormous pressure on any manufactures product particularly automotive is cost. Automotive companies require suppliers not only to be competitive but also require companies to have an active VA/VE programs (Value added/Value engineering), which over the life of a product will result in various cost downs during the life of the product. This result in very low margins and any improvements to the process are meant to be passed onto the customer. This is a "one way" arrangement and any mistake and subsequent cost up is not passed onto the customer, thus any issues that effects the profitability of the product must be treated with the upmost seriousness. Product must (to be profitable) brought into production as easily as possible.

This thesis is intended to be in part used in the design process to minimise the chance of any miscalculations moving through the design stage which may result a major operating flaw in the production process.

Southern Aluminium Pty Ltd is a manufacturer of automobile wheels and is a wholly owned subsidiary of Comalco Aluminium Ltd. Comalco, a 67% subsidiary of Rio Tinto (formally CRA), has operations that produce a high percentage of Australia's bauxite and a large percentage of Australia's primary aluminium. Include in its operations are 3 primary aluminium smelters one (the groups oldest) exist adjacent to Southern Aluminium in the North of Tasmania near the deep-sea port of Bell Bay. The other two smelters are located in New Zealand and Queensland. The combined production of all 3 smelter is near 700,000 tonnes/annum and dependant on commercial forces this production output can be met.

Southern Aluminium was established in 1989 having to meet production in excess of 50,000 wheels per month for the world automobile industry. Southern Aluminium was established when Comalco had a deliberate policy of supporting value-added activities outside of its smelter operations. Comalco has since changed its philosophy on value adding outside of the smelter operations and as a consequence of this Southern Aluminium is now in the process of being sold.

Southern Aluminium customers include well-established automobile manufacturing companies such as Nissan, Mazda, Mitsubishi and Ford. Southern Aluminium produce a variety of wheel types and offer a complete package in design from initial renderings from the customer through, casting, machining and finishing of aluminium wheels. The company has developed a consistent theme of quality awareness throughout the plant and a philosophy of process control and quality assurance.

Aluminium is a material that offers excellent resistance to corrosion in the environment expected for an automobile wheel it achieves good strength and ductility making it an ideal material for the requirements of an aluminium wheel.

The properties aluminium alloy 601 possesses make it a most suitable material for all stages of the automobile wheel manufacturing process, including casting, heat treating, machining, and finishing with subsequent improvement in service life.

All wheels at Southern Aluminium are produced using commercial aluminium alloy 601. The constituents added to aluminium to produce alloy 601 are approximately by weight 7% silicon, 0.3% magnesium, and 0.005% strontium, making the alloy predominantly an aluminium-silicon-magnesium system. Aluminium alloy 601 is used as the work material at Southern Aluminium due to its consistent mechanical properties and structural integrity in permanent mould castings, this material is also specified by customers.

There is several Characteristics that make an aluminium wheel preferable to steels wheels traditionally used, these advantages include:

1. *Aluminium wheels have higher cosmetic value than the alternate steel wheels.*

2. *Alloy wheels can in some circumstance be lighter than their steel counterparts, which has certain advantages for handling on vehicles by lowering the unsprung weight.*

3. *Alloy wheels are produced in a lathe. Rolling the rim produces steel wheels. The later process has poor capability in producing good runout results. Alloy rims are produced using a lathe. Subsequently an alloy wheel has excellent runout results.*

4. *Aluminium has a higher thermal transfer coefficient. This can result in lower hub temperatures, with subsequently better brake and tyre performance.*

In combination of the above effects the use of aluminium alloy wheels can improve tyre safety and wear with improved braking characteristics.

The manufacturing process employed at Southern Aluminium is now briefly demonstrated in the form of a flow chart and description.

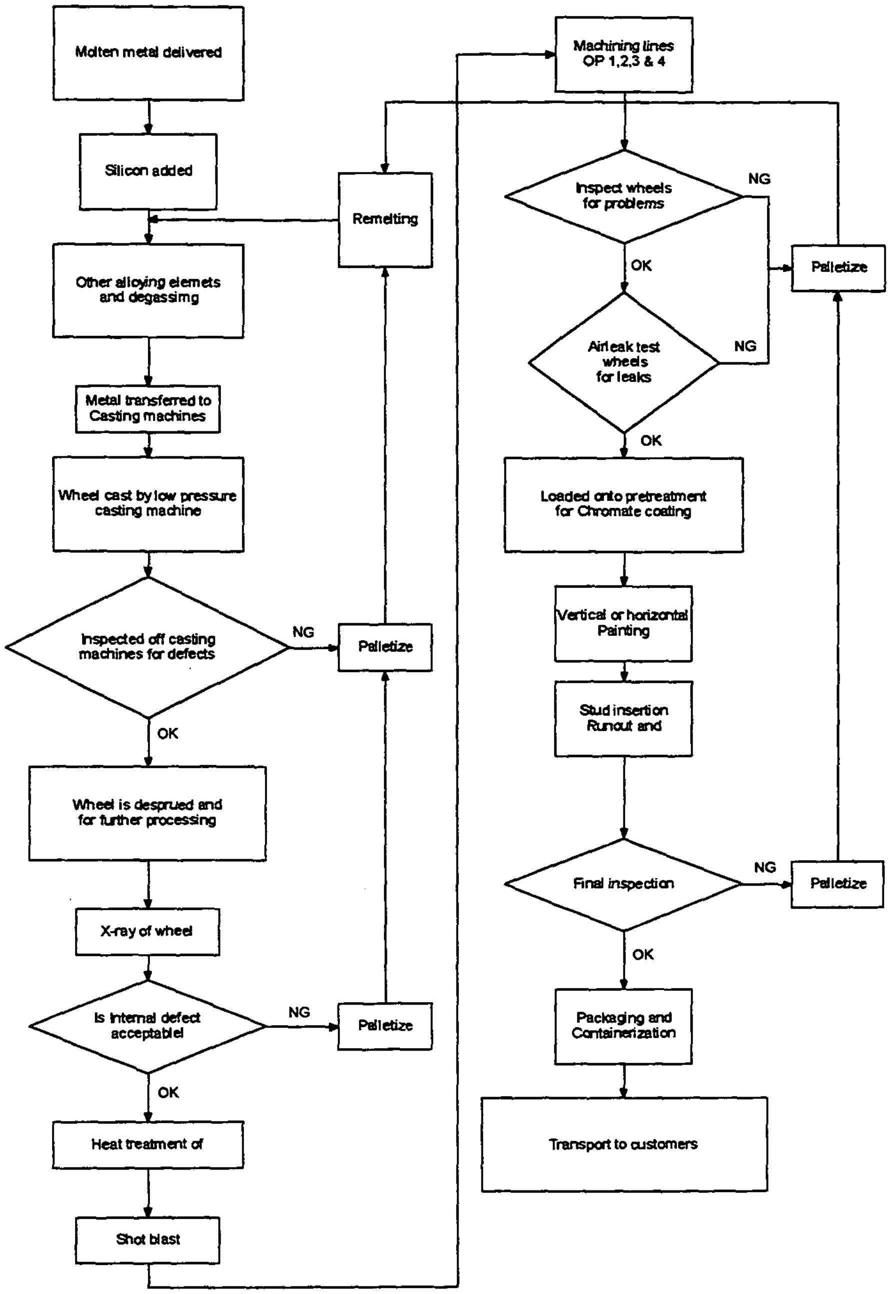


Figure 1. The process flow chart as a representation of the Southern Aluminium manufacturing process

Molten aluminium is delivered to Southern Aluminium, as it is needed, from the nearby aluminium smelting plant. It is delivered in large crucibles that are able to maintain the molten temperature during transportation. The molten aluminium is kept in large holding furnaces where it is alloyed up with the main alloying component of 601, that is silicon. The material is then transferred into smaller mobile crucibles, known as 'transfer crucibles' where the final alloying and metal cleaning processes occur. The metal cleaning process referred to is a degassing process in which an inert gas, Argon is passed through the metal in a finely dispersed bubble mixture. This process then removes the major contaminating elements of hydrogen and metallic oxides.

Following on from the initial molten metal preparation and filling of the casting machine crucibles there are four major operations that contribute to the manufacturing of a wheel at the plant. These are casting, heat treatment, machining and finishing. Each of these four major operations involves a series of smaller individual operations. Figure 1 shows product flow, involving these four major stages of production, throughout the plant.

It can be seen from the product flow chart that the first major stage in the wheel manufacturing process is casting. Wheels are cast using a low-pressure die casting process, the principles of which are discussed later. The plant has eight low-pressure die casting machines in total, which are grouped together as four pairs. A single operator is responsible for the operation of one casting machine, each casting machine has 2 cavities or moulds. A human operator pressing the appropriate buttons on the casting machine control panel initiates each casting cycle. A casting cycle involves filling of the dies with molten aluminium, solidifying the aluminium in the dies, ejecting the solidified castings from the dies, quenching the castings to a temperature close to room temperature and delivering the castings to the operator for further processing. When running at full capacity, each casting machine is capable of producing two castings simultaneously every six minutes. Each metal transfer into the caster crucible yields enough volume of metal for the production of approximately sixty wheels. The operator that initiates the casting cycle is responsible for some further wheel processing operations. These operations include the stamping of each cast wheel with a melt number stamp, manually removing any visible marks from the front face of each wheel, manually removing excess aluminium from the top and bottom rim of each wheel and finally, checking the castings for distortion using a distortion gauge. A melt number stamp is essential on each cast wheel so that the alloy content of the wheel can be identified if needed.

Each time the caster crucible is filled an alloy sample is taken from the crucible and examined spectrographically to determine alloy composition. The alloy composition is recorded and the melt number is changed. The melt number on each cast wheel can then be related to an exact alloy composition. A distortion gauge placed on the front face of a wheel will inform the operator of the wheel distortion. A wheel that is badly distorted, greater than plus or minus half a millimetre out of plane, is rejected immediately. Molten metal is fed at low pressure from the caster crucible through a tube into the centre of the bottom die and continues to be fed into the die until sufficient metal has entered to fill the cavity. A fine steel wire mesh is placed into the centre of the bottom core of each die prior to initiating the casting cycle to prevent impurities entering the casting. Any impurities in the molten aluminium present in the caster crucible become caught in the wire mesh during the casting cycle and solidify. This solidified form stays attached to the casting as it is removed from the die. This solidified form, containing impurities and the fine steel wire mesh, is known as a 'sprue' and is removed from each casting using an automated drilling operation. In this operation, a wheel is fed automatically from the casting machine, via a conveyor, into the drilling machine. Inside the drilling machine the wheel is clamped automatically, drilled to remove its sprue and machined across the back of the rim to remove excess flashing.

The wheel is then automatically delivered to another conveyor where it travels to the x-ray machine. At the x-ray machine, the wheel undergoes x-raying to determine porosity content and other possible defects. An operator watches the wheel as it is x-rayed and determines at the end of the x-raying cycle whether or not the wheel must be rejected by comparing the wheel porosity content with a sample showing the maximum porosity size and scattering allowed. X-raying is the final operation in the casting section of the plant. Material handling between processes is highly automated in the casting section of the plant. The high degree of automated wheel handling also means that there is much faster and more consistent transfer of wheels between subsequent processes than there could be without automated material handling.

The strength and hardness properties of a wheel directly after casting are not sufficient to meet customer specifications. Wheel properties in the 'as-cast' condition do not meet the customer requirements

The 'as-cast' mechanical properties of a wheel can however be improved by subjecting the wheel to a heat treatment process. Heat-treated aluminium alloys are recognised under a temper designation system. For instance the heat treatment process employed at SAPL is designated as T6. T6 designation refers to the alloy going through a heat treatment schedule of 4 – 12 hrs at approximate temperatures of 540°C this is referred to as a solution treatment. This is then followed by a quench, normally into water.

Following the quench is a shorter period of heating at temperature approximating 150°C. This process is referred to as artificial aging. The specific heat treatment method adopted at Southern Aluminium is designated below.

Table 1 : Heat treatment process employed at SAPL

Process	Time	Temperature
Solution treatment	4.5 – 7.5 hrs	540 - 530°
Water Quench	As fast as practical	80°
Age	3 – 5 hrs	140°

The heat treatment process is a long process and constitutes the longest value added process in the plant. For this reason Southern places a lot of emphasis is place on the length of this process[2].

An operation used to give each wheel face a predetermined surface texture is called 'shot blasting'. Which follows immediately after heat treatment. During this operation wheels are struck repeatedly at high speed and force with small steel or balls, known as shot, of less than one millimetre diameter. An impression is left on the front face of the wheel after each strike of the shot. This results in a desired surface finish on the wheel that improves its visual appearance and aids in paint adhesion during painting operations carried out later in the processing cycle. Excess aluminium is removed from the wheel as a desirable secondary action during this operation due to the high speed and force at which the shot strikes the wheel. Surface machining of the wheel follows directly from shot blasting. Machining of wheels is a necessary step in the wheel manufacturing process as an 'as-cast' wheel is not of a satisfactory standard for commercial use.

Machining is used to shape wheels to a specified form and dimension, remove burrs and sharp edges remaining after casting and give the wheel a predetermined texture and surface finish. Machining consists of 4 or 5 operations. SAPL has 5 separate lines

[2] Work as completed by Fred Frost – Heat treatment of alloy wheels

each capable of performing these operations. Each machining line can be set-up to machine any one-wheel type at any given time. Each machining line is programmed for each wheel type produced at the plant. As there are five individual machining cells it is possible to carry out machining operations on five different wheel types at any one time. With this automated surface machining process, the only human intervention is the manual stacking of wheels at the end of the machine lines. To process a wheel through each of the machining operations mentioned earlier takes two to three minutes from start to finish. All machining operations are carried out automatically inside the machine and machined wheels are delivered to the operator at the end of the machine line, ready for further processing. The machining cells are the most advanced automated processing equipment in the plant and are an excellent example of how automation can save time, effort and money in a manufacturing system. Wheels delivered to the operator at the end of the machine lines are subject to a 'leak test' which involves immersing an air tight wheel completely underwater and viewing the water for escaping air bubbles from the wheel rim section. Air bubbles escaping from a wheel indicates a defect in the wheel rim and thus the wheel must be rejected. The air leak test is a vital component of the wheel manufacturing process as wheels must not be allowed to leave the plant if they fail this test. Most of the tyres used in conjunction with aluminium wheels are tubeless so thus a wheel with an air leak fitted to a vehicle can be detrimental to passenger safety.

The final stage of wheel processing is finishing. The primary operations that fall into the category of finishing are detergent washing, spray painting (also wet painting), powder coating and paint curing of wheels and inspection and packaging of wheels for storage and shipment. Detergent washing of the wheels is necessary to ensure that the wheel is completely free from contaminants before painting. Wheels are delivered to the detergent washing centre on vertical hangers, which support two wheels only. The vertical hangers are contained on a continuous chain that runs through the detergent washing, powder coating and paint curing sections of the plant. The operations of detergent washing, powder coating and paint curing are completely automated once the wheels are manually stacked on the vertical hangers by operators from the finishing area. Wheels that require spray painting are manually taken from the vertical hangers and fed onto a horizontal chain that runs through the spray painting centre. Spray painting is also an automated process that requires human involvement only for the stacking and removing of wheels from the horizontal chain and the initial setting up of the spray painting guns. Once spray painted, the wheels are returned to the vertical hangers from which they were taken. Wheels then continue through to the powder coating and paint curing operations. Powder coating is an operation that covers the surface of each wheel with a thin layer of paint in powder form. To harden the powder on the wheel it is necessary to subject the wheel to a paint curing operation. During paint curing, wheels travel through an oven set at nominally 190°C for approximately thirty minutes during which time the powder forms a hard, clear coating on the wheel. After paint curing the wheels are manually removed from the vertical hangers, stacked onto pallets and stored until required for final inspection. Some wheel types, depending on their shape, may require painting directly after shot blasting and prior to machining. Wheels that do require spray painting before machining are still powder coated and inspected after machining, as demonstrated on the product flow chart in Figure 1. Final inspection of the wheels involves an operator visually examining each wheel and deciding whether or not the wheel can be shipped depending on its condition. At final inspection, wheels may be rejected or sent for rework or reface if they are not of an acceptable standard to send to the customer. Some common problems that cause a wheel to be rejected or sent for rework or reface at final inspection include paint defects, discovery of defects not noticed earlier during processing or damage to the front face of the wheel.

Automation of processes and automated material handling plays a very important role in the manufacturing of wheels at Southern Aluminium. Transfer of wheels between substations in the casting, heat treatment and machining sections of the plant is carried out with automated material handling systems such as conveyors, sensors and mechanical grippers, thus leading to the need for very little human interaction.

There is human handling and inspection of wheels between most operations. The possibility of discovering a reject wheel is facilitated throughout most of the manufacturing cycle, figure 1 shows the fundamentals of the process but does not demonstrate the entire process or manufacturing philosophy. For example rejection of rejects is encouraged at any stage in the process to minimise processing of a defective wheels. The flow chart provides shows only the main defect detection points. It is, however, more desirable to discover a reject wheel early in the manufacturing process rather than later. This is because the value added component increases with every process step, if a value added step occurs prior to defect detection it is money lost to the organisation. That is, for every step of successful processing that a wheel undergoes it will increase in value to the company until such time that it is ready for shipment. To reject a wheel after painting or machining is much more costly to the company than to reject a wheel at the casting stage. All reject wheels are remelted at the plant. Reworking and refacing of wheels are alternative operations to rejection for some wheels. These operations often involve re-machining or sanding the front face of a wheel to remove micro-porosity of minor defects. Reworking and refacing are again costly and undesirable operations but are sometimes necessary and are cheaper options to rejecting a wheel. Reworked and refaced wheels need only to undergo a few reprocessing operations before they are ready for shipment whereas a reject wheel must be melted and totally reprocessed. Southern Aluminium is a quality-accredited company that strives for quality but the production of some reject wheels is inevitable. To achieve one hundred percent quality in the manufacturing process and eliminate tasks not on the critical path of processing, such as reject, rework and reface, is an ultimate goal of every company in theory but is, however, unlikely to be achieved in practice. Continual improvement and reduction of rejects as a result of research and development is an ongoing task at Southern Aluminium.

To ensure product control a range of non-destructive and destructive testing. is maintained. Apart from essential quality control requirements stipulated by Southern Aluminium's customers, the company institutes a number of additional internal manufacturing process and quality control procedures to minimise work-in-progress scrap throughout the manufacturing cycle. It is useful here to introduce the control points that are critical points to demonstrate the manufacturing process and the controls that are introduce to ensure the quality. It is worth noting the Southern works to Total Quality Management. This refers to the fact that all parts of the operation are responsible for quality. Southern does not have a quality control department but has a quality assurance group, which is essentially very small.

A process that is ill performed early is incredibly expensive to an organisation. It is common (or has been) within manufacturing to "band aid" many of the failings of the product/process design. The normal approach with many manufacturing operations is to "inspect out" or fail the components in service. This is not smart manufacturing. It is now expected in the automotive industry to improve your process during the life of a project by tackling the root cause problems and fixing them. In the automotive industry these gains to be shared with the customer. If flexible manufacturing is allowed to flourish and improve itself this can result in a win/win position.

It is concerned with selecting methods of production, tooling, fixtures and machinery, sequencing of operations and assembly. Two aspects of process planning are specification of a suitable production schedule and determining production speeds for minimum cost and maximum production rate. Process planning determines product flow within a manufacturing system. Product flow is the flow of product throughout the manufacturing system from initial to finished product. Factors that influence product flow are the sequencing of necessary production operations to give the most efficient process, plant layout and the ordering of operations such that necessary tasks are completed in the correct order of processing. Product flow analysis assists in achieving the most economical use of floor space and is used to assess sequencing of operations to determine the optimum arrangement of equipment. In its broadest sense, product flow is used to analyse products flowing through a plant and assess the most appropriate paths and sequencing of events. The study of product flow within a manufacturing environment involves the optimisation of a problem by analysis of all the options and alternatives within the problem. It is very important that the focus of the problem remains the desire for an increase in productivity. There is a need for understanding product flow and process planning as a part of controlling and optimising overall production time and production rate. Without efficient product flow productivity cannot be optimum. Improvements that arise from product flow analysis contribute to the productivity improvements of the operation.

As shown in figure 1 the first part of the process is casting. If this process is not performed satisfactorily or performed incorrectly the potential for the error to be multiplied through the process specifically in cost is enormous. This is why successful introduction of product into the casting process is essential for a successful business.

The basis of this thesis is to provide a methodology for improved design involving minimum effective thickness in casting and process development, which will enable the most successful introduction of product into the business and hence give the business the highest possible chance of profitability.

CHAPTER 2

LITERATURE SURVEY

Casting is one of the oldest manufacturing processes, and even today it is the first step in manufacturing most products [3,4]. With number of process variables involved during this manufacturing process, casting can be difficult to 'get it right'. In the casting process, the material is first liquefied by properly heating it in a suitable furnace. Then, the liquid is poured into a previously prepared mould cavity where it is allowed to solidify. Subsequently, the product is taken out of the mould cavity, trimmed, and cleaned to shape. The liquid metal influences and is influenced by its environment, exchanging alloys, impurities, and gas. The surging and tumbling flow of the molten liquid can introduce bubbles that create imperfections in the final casting. There is a need to exercise control during the freezing and subsequent cooling stages to ensure less distortion. The solidified casting strives to contract whilst being resisted by the mould. The casting when not properly carried out can result in excessive internal stresses and strains that can lead to failure. In this chapter a brief review of aluminium alloy casting is carried out with a view to highlighting the effect of major process variables on the casting performance. A brief review of casting processes is carried out before the detailed study of the aluminium alloy casting.

It is clear from the definition of the process that a successful casting operation needs knowledge in the following areas:

1. *Preparation of moulds and patterns (used to make the mould).*
2. *Melting and pouring of the liquefied metal.*
3. *Solidification and further cooling to room temperature.*
4. *Defects and inspection.*

There are various types of casting processes depending, among others, on the material, the type of patterns and moulds, and the pouring technique.

Some of the basic common features among the various casting processes in the context of the four areas are discussed below:

The suitability of the casting operation for a given material depends on:

1. The melting temperature of the job and the mould materials,
2. The solubility of and the chemical reaction between the job and the mould materials,
3. The solubility of the atmosphere in the material at different temperatures to be encountered in the casting operation,
4. The thermal properties such as conductivity and coefficient of linear expansion of both the mould and job materials.

2.1 Pattern and Mould's

A pattern is the replica of the part to be cast and is used to prepare the mould cavity. Patterns are made of either wood or metal [4]. A mould is an assembly of two or more metal blocks, or bonded refractory particles (sand) consisting of a primary cavity. The mould cavity holds the liquid material and essentially acts as a negative of the desired product. The mould also contains secondary cavities for pouring and channelling the liquid material into the primary cavity and to act as a reservoir, if necessary.

A four-sided frame in which a sand mould is made is referred to as a flask. If the mould is made in more than one part, the top portion is called the cope and the bottom one is termed as the drag. For producing hollow sections, the entry of the liquid metal is prevented by having a core in the corresponding portion of the mould cavity. The projections on the pattern for locating the core in the mould are called core prints. There are diverse types of patterns and moulds depending on the material, the job, and the number of castings required.

2.1.1 Pattern Allowances

A pattern is always made somewhat larger than the final job to be produced. This excess in dimensions is referred to as the pattern allowance. There are two categories of pattern, namely, the shrinkage allowance and the machining allowance.

The shrinkage allowance is provided to take care of the contractions of a casting. The total contraction of a casting takes place in three stages, and consists of:

(i) The contraction of the liquid from the pouring temperature to the freezing temperature,
(ii) The contraction associated with the change of phase from liquid to

solid,

(iii) The contraction of the solid casting from the freezing temperature to room temperature.

It must be noted, however, that it only the last stage of the contraction which is taken care of by the shrinking allowance. Obviously, the amount of shrinkage allowance depends on the linear coefficient of thermal expansion α_1 of the material. The higher the value of this coefficient, the more the value of shrinkage allowance.

Usually, a cast surface is too rough to be used in the same way as the surface of the final product. As a result, machining operations are required to produce the finished surface. The excess in the dimensions of the casting (and consequently in the dimensions of the pattern) over those of the final job to take care of the machining is called the machining allowance [5]. The total machining allowance also depends on the material and the overall dimension of the job, though not linearly as the shrinkage allowance.

There is another deviation from the original job dimensions and is intentionally provided in the pattern; this is called draft. It refers to a taper put on the surface parallel to the direction of withdrawal of the pattern from the mould cavity. A draft facilitates easy withdrawal of the pattern. The average value of the draft is between ½° and 7° [5,6,7].

2.1.2 Types of Patterns.

The commonly-used patterns are classified as follows:

(i) Loose pattern. It is made in one piece, usually from wood, and is used for castings numbering up to 100.

(ii) Gated pattern. This is simply one or more than one loose pattern with attached gates and runners and provides a channel through which the molten metal can flow from the pouring sprue to the mould cavity. This pattern is frequently set on a follow board conforming to the parting surface of the mould. The follow board helps in an easy removal of the pattern after the mould has been prepared.

(iii) Match plate pattern. This pattern is made in two halves mounted on both sides of a match plate (of wood or metal) conforming to the contour of the parting surface. The match plate is accurately placed between the cope and the drag flasks by means of locating pins. For small castings, several patterns can be mounted on the same match plate.

(iv) Cope and drag pattern. Here, the cope and drag halves of a split pattern (Fig 2.1) are separately mounted on two match plates. Thus, the cope and the drag flasks are made separately and brought together (with accurate relative location) to produce the complete mould.

(v) Sweep pattern. Normally made of wood, it is used to generate surfaces of revolution in large castings, and to prepare moulds out of a paste-like material. Here, 'sweep' refers to the section that rotates about an edge to yield circular sections.

(vi) Skeleton pattern. This consists of a simple wooden frame outlining the shape of the casting. It is used to guide the moulder for hand-shaping the mould and for large castings having simple geometrical shapes.

While designing a pattern, the parting line should be chosen so as to have the smallest portion of the pattern in the cope. As the moulding sand has greater strength in compression than in tension, the heaver sections of the pattern should be included in the drag. The possible defects due to loose sand in the mould are more frequent in the cope hald. For this reason, the most critical surface should also be included in the drag.

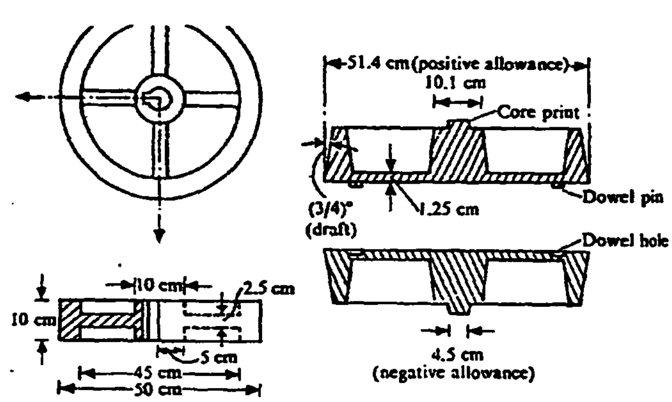


Figure 2.1: Cast iron wheel and its split pattern (shown to a different scale) [7].

Figure 2.1 shows a typical split pattern (with allowances) for a cast iron wheel. The reader is advised to carefully note all the allowances, positive and negative.

2.1.3 Types of Moulds

Moulds can be classified on the basis of either the material, i.e. green sand mould, plastic mould, metal mould, or on the method of making them, e.g., shell mould and investment mould. Metal moulds are permanent in the sense that a large number of castings can be made from a single mould; on the other hand, moulds of refractory materials can be used only once. Generally, the green sand moulds are used; in what follows, we shall consider some of their important characteristics.

2.1.3.1 Green Sand Mould

The material for a green sand mould is a mixture of sand, clay, water and some organic additives, e.g. wood flour, dextrin, and sea coal. The percentage of these ingredients on weight basis is approximately 70-85% sand, 10-20% clay, 3-6% water, and 1-6% additives. This ratio may vary slightly depending on whether the casting is ferrous or nonferrous.

Sand is an inexpensive refractory material, but natural sand may not have all the desirable qualities of a moulding material. For example, it normally has higher clay content than desired. The sand used as a moulding material should have a specified clay, water, and additive content; in addition, it must have a specific grain size distribution. The importance of the grain size distribution would be clear from the discussion that follows.

Both the shape and the size of sand grains vary over a wide range. The grains may be smooth and round in shape or may have sharp angular corners. The bulk density of a sand-mix is very low if the grains result an increased void and a higher permeability. Higher permeability permits an easy outflow of the gases (produced during the casting operation) which may otherwise be entrapped within the casting. The situation gets reversed if the grains are of various sizes and have sharp corners. To study the grain size distribution, the screening test is performed. This is done by taking a fixed sample weight of sand and screening it through standard sieves. The screening is accomplished by shaking the sieves. The amount of sand that collects in the different sieves is then plotted. Finally, from this plot, the distribution of grain size and the average grain size are computed.

Clay, together with water, acts as a bonding agent and imparts tensile and shear strength to the moulding sand. The organic additives burn out at high temperatures and make room for the moulding sand to expand, and thus save the mould from crumbling.

The success of a casting process depends greatly on the properties of the moulding sand. These include (i) strength, (ii) permeability, (iii) deformation, (iv) flowability, and (v) refractories. (Standard specimens and tests are recommended for an evaluation of these properties). Strength refers to the compressive strength and deformation indicates the change in length of a standard specimen at the point of failure. Permeability is expressed as the gas flow rate through the specimen under a specified pressure difference across it. Flowability refers to the ability of the sand to flow around and over the pattern when the mould is rammed. Refractoriness measures the ability of the sand to remain solid as a function of temperature. For a given sand-clay ratio, the nature of variation of these properties with water content is as shown in Fig. 2.2. It is obvious, both from strength and permeability considerations, that there is an optimum water content. At a low water content, dry clay powder, being finer than sand grains, fills up the void between the sand particles, and thus reduces

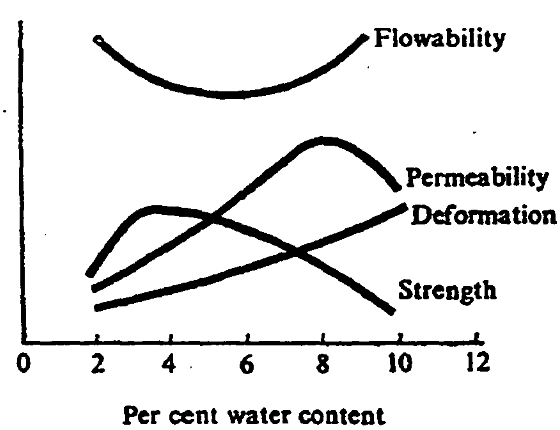


Figure 2.2: Effect of water content on moulding sand properties

the permeability. With higher water content, moist clay forms a coating over the sand particles keeping them further away, thus enhancing the permeability. Beyond the optimum water content, water itself fills up the void and reduces the permeability.

2.1.3.2. Preparation of Mould

Moulds are made by hand if the number of moulds to be prepared is small. If a large number of simple moulds are required, moulding machines are then used. In this section, we shall briefly discuss some important features of mould making; also, some typical moulding machines will be outlined.

To facilitate an easy removal of the pattern, a parting compound, e.g., nonwetting talc, is dusted on the pattern. Fine grain facing sand is used to obtain a good surface on the casting. Normally, a dead weight is placed on the cope flask to prevent the cope flask from floating due to hydrodynamic forces of the liquid metal. For a large mould, care should be taken to prevent the sand from falling off the cope flask when it is lifted to remove the pattern. This can be done by providing extra supports, called gaggers, within the cope flask. For a casting with re-entrant surfaces, e.g. a wheel with a groove at the rim, the mould can be made in three parts (Fig 2.3). The part between the cope and the drag is termed as the cheek. For an easy escape of the gases, vent holes are provided in the cope flask.

The moulding machines operate on one or a combination of the principles explained in Fig 2.3. In jolt ramming, the mould is lifted through a height of about 5cm and dropped 50-100 times at a rate of 200 times per minute. This causes somewhat uneven ramming, but is quite suitable for horizontal surfaces. On the other hand, squeezing is found satisfactory for shallow flasks. The sand slinging operation is also very fast and results in uniform ramming. This, however, incurs high initial cost.

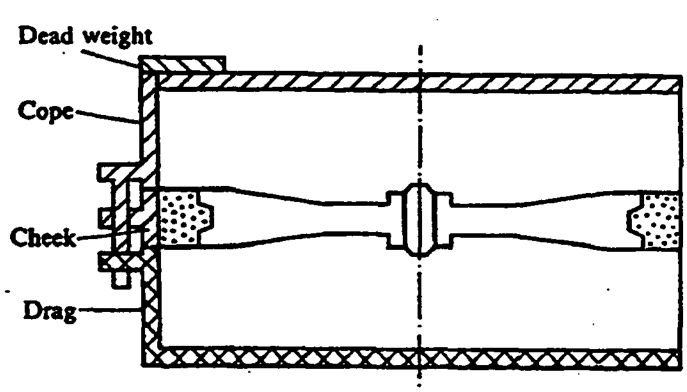


Figure 2.3: Principles of machine moulding operation

2.1.3.2 Permanaent moulds.

Permanent moulds are predominantly used for high productivity simple shaped castings [17]. Molten metal is introduced into the mould under gravity or with low-pressure assist. Aluminium, magnesium, zinc, lead, copper-base alloys are the principal alloys cast.

The process works best in continuous operation so that the mould temperature can be maintained within a fixed operating range. Operating temperature of the mould is one of the most important factors in successful permanent mould casting [17] . Metal moulds are associated with the die-casting industry.

2.2 Melting and metal

A proper care during melting is essential for a good, defect-free casting. The factors to be considered during melting include gases in metals, selection and control of scrap, flux, furnace and temperature.

2.2.1 Pouring (Gating Design)

After melting, the metal is poured or injected into the mould cavity. We shall now discuss the difficulties faced in doing this and explain how these can be overcome by using an appropriate gating design. A good gating design ensures distribution of the metal in the mould cavity at a proper rate without excessive temperature loss, turbulence, and entrapping gases and slags.

If the liquid metal is poured very slowly, then the time taken to fill up the mould is rather long and the solidification may start even before the mould has been completely filled up. This can be avoided by using too much superheat, but then gas solubility may cause a problem. On the other hand, if the liquid metal impinges on the mould cavity with too high a velocity, the mould surface may be eroded. Thus, a compromise has to be made in arriving at an optimum velocity.

The design of a gating system depends on both the metal and mould compositions. For example, an elaborate gating design is needed to avoid dross (e.g. oxides) in easily oxidized metals of low melting point such as aluminium. For cast iron, however, a short path for the liquid metal is selected to avoid a high pouring temperature. The gating design for a ceramic mould is quite different from that normally used for a permeable sand mould.

Broadly, gating designs can be classified into three categoeis, namely, (i) vertical gating, (ii) bottom gating, and (iii) horizontal gating. In vertical gating, the liquid metal is poured vertically to fill the mould with atmospheric pressure at the base. In bottom gating, on the other hand, the liquid metal is filled in the mould from bottom to top, thus avoiding the splashing and oxidation associated with vertical gating. Figure 2.4 shows a simple vertical gating and a bottom gating design. In the horizontal gating system, additional horizontal portions are introduced for better distribution of the liquid metal with minimum turbulence.

Simple calculations based on principles of fluid flow can lead to an estimate of the time taken to fill up a mould. We shall illustrate this for the two designs in Fig. 2.5. The integrated energy balance equation on the basis of per unit mass flow, more commonly known as Bernoulli's equation, will be used. For example, in Fig. 2.6a, it is assumed that the pressure at points 1 and 3 is equal (i.e. $p_1 = p_3$) and that level 1 is maintained constant. Thus, the velocity at station 1 (v_1) is zero. Moreover, the frictional losses are neglected. Then, the energy balance equation between points 1 and 3 gives

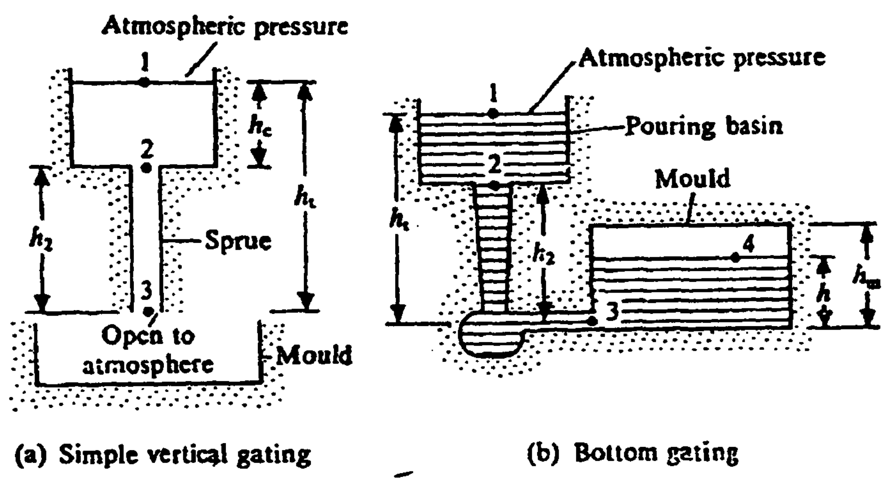


Figure 2.4 Types of gatings – gravity die casting

$$gh_t = v_3{}^2 / 2$$

or $$v_3 = \sqrt{2gh_t}$$

where g is the acceleration due to gravity and v_3 is the velocity of the liquid metal at the gate, subsequently referred to as v_g. So, the time taken to fill up the mould (t_f) is obtained as:

$$t_f = \frac{V}{A_g v_3}$$

where A_g and V are the cross-sectional area of the gate and the volume of the mould, respectively.

In Fig 2.4b, applying Bernoulli's equation between points 1 and 3, we get

$$gh_t = \frac{p_3}{\rho_m} + \frac{v_3^2}{2}$$

where ρ_m is the density of the liquid metal, p_3 is the gauge pressure at station 3, and h_t is again assumed to be constant. Further, applying Bernoulli's equation between points 3 and 4, with the assumptions that v_4 is very small and all the kinetic energy at station 3 is lost after the liquid metal enters the mould, we can write

$$p_3 / \rho_m = gh.$$

From the last two equations, the velocity of the liquid metal at the gate we obtain is

$$v_g = v_3 = \sqrt{2g(h_t - h)}$$

The last equation gives the velocity of a jet discharging against a static head h, making the effective head as $(h_t - h)$. Now, for the instant shown, let the metal level in the mould move up through a height dh in a time interval dt; A_m and A_g are the cross-sectional areas of the mould and the gate, respectively. Then,

$$A_m dh = A_g v_g dt$$

Using the last two equations, we get

$$\frac{1}{\sqrt{2g}}\frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m}dt$$

At $t = 0$, $h = 0$ and at $t = t_f$ (filling time), $h = h_m$. Integrating the last equation between these limits, we have

$$\frac{1}{\sqrt{2g}}\int_0^{h_m}\frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m}\int_0^{t_f} dt$$

or $$t_f = \frac{A_m}{Ag}\frac{1}{\sqrt{2g}}2\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right)$$

If a riser (reservoir to take care of the shrinkage from the pouring temperature) is used, then the pouring time t_f should also include the time needed to fill up the riser. Normally, open risers are filled up to the level of the pouring sprue; thus, the time taken to fill up the riser is calculated with A_m replaced by A_r (riser cross-section) and h_m by h_t in the last equation.

2.3 Defects in Castings

Different types of defects in castings, and their origin are briefly discussed in this section.

The following defects are most commonly encountered in the sand mould castings (Fig 2.5):

(i)Blow. It is a fairly large, well-rounded cavity produced by the gases which displace the molten metal at the cope surface of a casting. Blows usually occur on a convex casting surface and can be avoided by having a proper venting and an adequate permeability. A controlled content of moisture and volatile constituents in the sand-mix also helps in avoiding the blow holes.

(ii) Scar. A shallow blow, usually found on a flat casting surface, is referred to as a scar.

(iii) Blister. This is a scar covered by the thin layers of a metal.

(iv) Gas holes. These refer to the entrapped gas bubbles having a nearly spherical shape, and occur when an excessive amount of gases is dissolved in the liquid metal.

(v) Pin holes. These are nothing but tiny blow holes, and occur either at or just below the casting surface. Normally, these are found in large numbers and are almost uniformly distributed in the entire casting surface.

(vi) Porosity. This indicates very small holes uniformly dispersed throughout a casting. It arises when there is a decrease in gas solubility during solidification.

(vii) Drop. An irregularly-shaped projection on the cope surface of a casting is called a drop. This is caused by dropping of sand from the cope or other overhanging projecttions into the mould. An adequate strength of the sand and the use of gaggers can help in avoiding the drops.

(viii) Inclusion. It refers to a nonmetallic particle in the metal matrix. It becomes highly undesirable when segregated.

(ix) Dross. Lighter impurities appearing on the top surface of a casting are called dross. It can be taken care of at the pouring stage by using items such as a strainer and a skim bob.

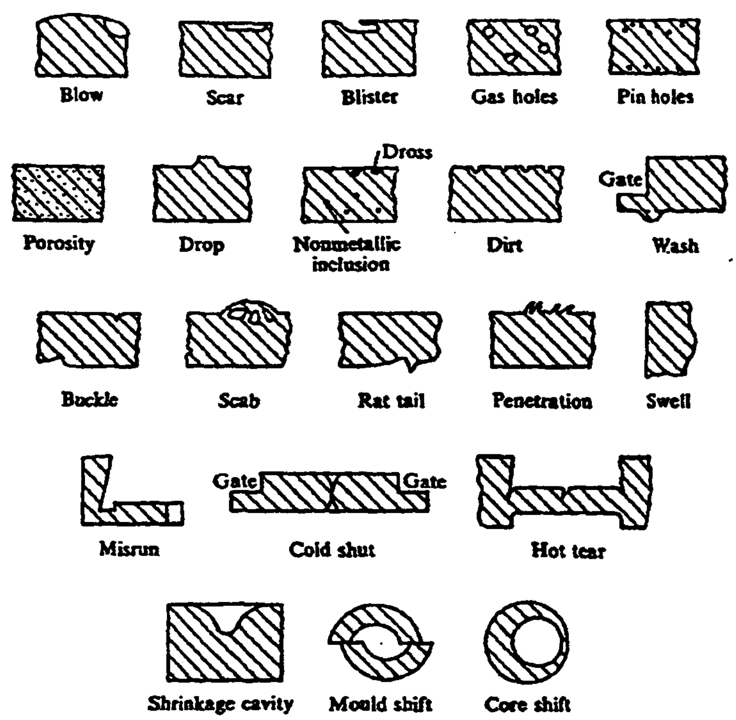


Figure 2.5: Common casting defects

(x) Dirt. Sometimes sand particles dropping out of the cope get embedded on the top surface of a casting. When removed, these leave small, angular holes, known as dirts. Defects such as drop and dirt suggest that a well-designed pattern should have as little a part as possible in the cope. Also, the most critical surface should be placed in the drag.

(xi) Wash. A low projection on the drag surface of a casting commencing near the gate is called a wash. This is caused by the erosion of sand due to the high velocity jet of liquid metal in bottom gating.

(xii) Buckle. This refers to a long, fairly shallow, broad, vee-shaped depression occurring in the surface of a flat casting of a high temperature metal. At this high temperature, an expansion of the thin layer of sand at the mould face takes place before the liquid metal at the mould face solidifies. As this expansion is obstructed by the flask, the mould face tends to bulge out, forming the vee shape. A proper amount of volatile additives in the sand-mix is therefore essential to make room for this expansion and to avoid the buckles.

(xiii) Scab. This refers to the rough, thin layer of a metal, protruding above the casting surface, on top of a thin layer of sand. The layer is held on to the casting by a metal stringer through the sand. A scab results when the upheaved sand is separated from the mould surface and the liquid metal flows into the space between the mould and the displaced sand.

(xiv) Rat tail. It is a long, shallow, angular depression normally found in a thin casting. The reason for its formation is the same as that for a buckle. Here, instead of the expanding sand upheaving, the compressed layer fails by one layer, gliding over the other.

(xv) Penetration. If the mould surface is too soft and porous, the liquid metal may flow between the sand particles up to a distance, into the mould. This causes rough, porous projections and this defect is called penetration. The fusion of sand on a casting surface produces a rough, glossy appearance.

(xvi) Swell. This defect is found on the vertical surfaces of a casting if the moulding sand is deformed by the hydrostatic pressure caused by the high moisture content in the sand.

(xvii) Misrun. Many a time, the liquid metal may, due to insufficient superheat, start freezing before reaching the farthest point of the mould cavity. The defect that thus results is termed as a misrun.

(xviii) Cold shut. For a casting with gates at its two sides, the misrun may show up at the centre of the casting. When this happens, the defect is called a cold shut.

(xix) Hot tear. A crack that develops in a casting due to high residual stresses is called a hot tear.

(xx) Shrinkage cavity. An improper rister may give rise to a defect called shrinkage cavity, as already detailed.

(xxi) Shift. A misalignment between two halves of a mould or of a core may give rise to a defective casting, as shown in Fig 2.7. According, this defect is called a mould shift or a core shift.

2.4 Other Casting Processes

We have so far discussed the basic features of the casting processes mainly with reference to the most common type of green sand mould casting. In this section, we shall consider the other types of casting processes.

2.4.1 Dry Sand Mould Casting

The dry sand mould casting uses expendable moulds, i.e. each mould is used only once. A dry sand mould is basically a green sand mould baked in an oven at 100-250°C for several hours. The sand-mix contains 1-2% of pitch. The oxidation and polymerization of pitch increases the hot strength of the mould. As the water is driven out from the sand-mix by heating, the defects caused by the generation of steam, e.g. blows and porosity, are less frequent in dry sand mould casting.

2.4.2 Shell Mould Casting

The shell mould casting is a semi-precise method for producing small castings repetitively in large numbers. The mould material contains phenolic resin mixed with fine, dry silica. These are mixed either dry or in the presence of alcohol; no water is used. Normally, a machined pattern of gray iron, aluminium, or brass is used in this process. First, the pattern is heated to 230-260°C, and then the sand-resin mixture is either dumped or blown over its surface. This way, the heated pattern melts and hardens the resin which, in turn, bonds the sand grains closely together. After a dwell time of 20-30 sec, the pattern and sand are inverted. When this happens, a layer of sand adheres to the pattern in the form of a shell of about 6mm thickness. The rest of the sand is cleaned off. The thickness of the shell can be accurately controlled by controlling the dwell time. The thickness of the shell is so decided that the shell has the required strength and rigidity to hodl the weight of the liquid metal to be poured into the mould. Then the mould is heated in an overn (at 300°C) for 15-60 sec. This curing makes the shell rigid when it can be stripped off by means of ejector pins mounted on the pattern. The shell thus formed constitutes one-half of the mould.

Two such halves, placed one over the other, make the complete mould. While pouring the liquid metal, the two halves are clamped down together by clamps or springs.

It should be noted that in this process, the smoothness of the mould wall is independent of the moulder's skill. This contributes to a better dimensional accuracy and consistency when compared with green sand moulding. Smooth mould walls also offer less resistance to the flow of liquid metal in the mould. This is why smaller gates can be used. Moreover, thin sections, sharp corners, small projections, which are not possible in green sand moulds, can be accommodated. Further, subsequent machining operations are also reduced. Often, only grinding can produce the finished product. The increased cost of the metal pattern (as compared with the wooden pattern used in green sand moulding), however, can be justified only if the casting is produced in large enough numbers.

2.4.3 Investment Casting

The process of investment casting is suitable for casting a wide range of shapes and contours in small-size parts, especially those that are made of hard-to-machine materials. The process produces excellent surface finish for the casting. Here, the mould is made in a single piece, and consequently there is no parting line to leave out fins. This also adds to the dimensional accuracy of the casting. As will be apparent from the description of the process, no complication arises when withdrawing a pattern from the mould. Though the process is elaborate and expensive, it has been found very suitable for casting turbine and jet engine parts made of high temperature and high strength alloys. We now describe the steps to be followed in this process.

A rather accurately dimensioned metal pattern is used. The dimensions of the pattern are calculated to compensate for the several size adjustments which take place in the process - in the die, in the wax, in the investment material, and, finally, in the casting material. The determination of the pattern dimensions is a tedious task and requires considerable experimentation. This makes the pattern in an investment casting very costly.

This pattern is used to make a die out of a soft material, e.g. aluminium. Thereafter, wax or plastic is injected into the die to form an expendable pattern. The expendable pattern is rinsed in alcohol to remove grease and dirt. After drying, the pattern is dipped in a slurry composed of silica flour, water, and some bonding agent. Then, the pattern is taken out of the slurry and rotated to produce a uniform coating, to fill inside corners and to drain out the excess slurry. Sometimes, a number of expendable patterns are assembled as a 'tree' for economy. Finally, fine-grain silica sand is sprinkled onto the wet slurry surface. The coating thus produced on the expendable pattern after drying is called a pre-coat.

The pattern with the pre-coat is then placed on a steel base and is covered by an open-ended steel can. Both the pattern and the can are secured to the base by molten wax. Then, the can is filled with a slurry of heavy, self-hardening refractory concentrate. The concentrate sets in after a lapse of 24 hours when the can is placed in an oven. Thus, most of the wax or plastic melts and flows out of the mould, leaving a cavity with the shape of the intended casting. The residual wax is removed by firing the mould in a furnace for about 24 hours.

The liquid metal is poured into this mould while it is still hot. This saves the liquid metal from acquiring the moisture and avoids high thermal gradient between the liquid metal and the mould. In critical cases, the pouring is conducted in a vacuum chamber or in a protective inert atmosphere (such as argon). Frequently, the mould is clamped to a special type of furnace which is then inverted for pouring directly from the furnace into the mould. After cooling, the can is removed and the hard refractory investment is knocked off by a hammer or other vibratory means. Finally, the adhered investment material is removed from the casting surface by sand-blasting or a tumbling operation.

2.4.4 Gravity Die Casting

In gravity die casting, a permanent mould is used. The liquid metal is poured into a non-expendable mould under the force of gravity. The process is normally used for cast iron and, occasionally, for a nonferrous casting. The mould is made of heat resistant cast iron, and is provided with fins on its outer surface for efficient air-cooling. The inner surface of the mould cavity is sprayed with an oil-carbon-silica mixture before each pouring.

2.4.5 Die Casting

In the die casting process, unlike in gravity casting, the liquid metal is forced into the mould cavity under high pressure. The process is used for casting a low melting temperature material, e.g. aluminium and zinc alloys. The mould, normally called a die, is made in two halves (see Figs 2.6-2.7) of which one is fixed and the other moving. Medium carbon, low alloy tool steel is the most common die material. The die is cooled by water for an efficient cooling of the casting. This also increases the die life. The process is referred to as a hot chamber or a cold chamber (Fig 2.8)

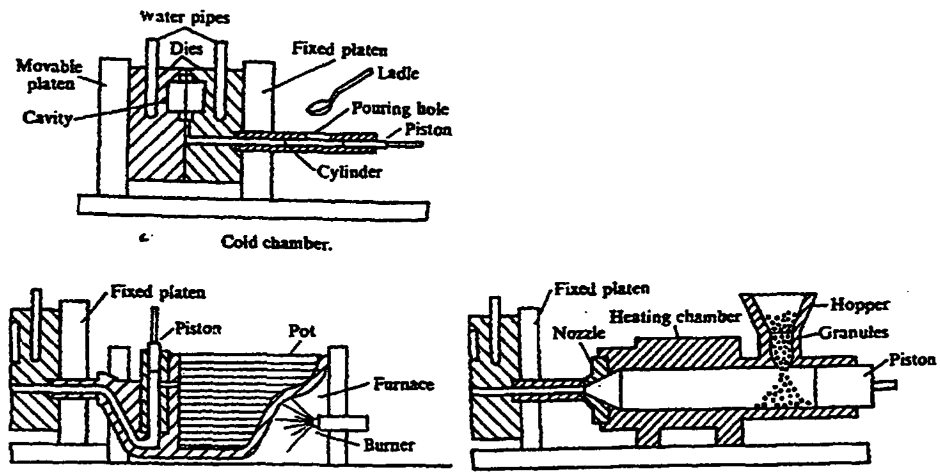


Figure 2.6 - 2.8 Cold and Hot Chambers and Injection moulding.

process, depending on whether or not the melting furnace is an integral part of the mould. Since the liquid metal is forced into the die with high external pressure, much thinner sections can be cast by this process. The process, when applied to a plastic casting, is called injection moulding.

2.4.6 Centrifugal Casting

The centrifugal casting process is normally carried out in a permanent mould which is rotated during the solidification of a casting (Fig 2.9). For producing a hollow part, the axis rotation is placed at the centre of the desired casting. The speed of rotation is maintained high so as to produce a centripetal acceleration of the order of 60g to 75g.

The centrifuge action segregates the less dense nonmetallic inclusions near the centre of rotation.

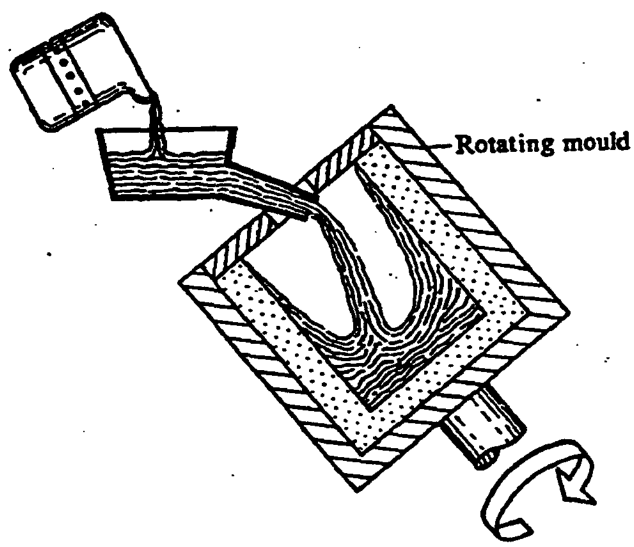


Figure 2.9: Centrifugal casting

It should be noted that the casting of hollow parts needs no core in this process. Solid parts can also be cast by this process by placing the entire mould cavity one one side of the axis of rotation. The castings, produced by this method, are obviously very dense. By having several mould cavities, more than one casting can be made simultaneously.

2.4.7 Low pressure die casting

Low-pressure die-casting is predominantly used for component manufacture. This includes a wide variety of components such as saucepans, wheels, heads, water pumps, etc. The fundamental advantage of low pressure is its ability to fill a cavity in a controlled manner via the riser tube. Once the die is full the pressure is increased aiding the feed to the cavity. It is normal to have only one feed point to the cavity. This is termed the sprue. The dies that form the cavity are usually multi component. The ability of the dies to eject the cavity and perform mechanical segregation is very important and in many ways more complex than the process itself. The basic principles of low pressure are diagrammatically shown below. A more detailed discussion of low-pressure die-casting is explained later .

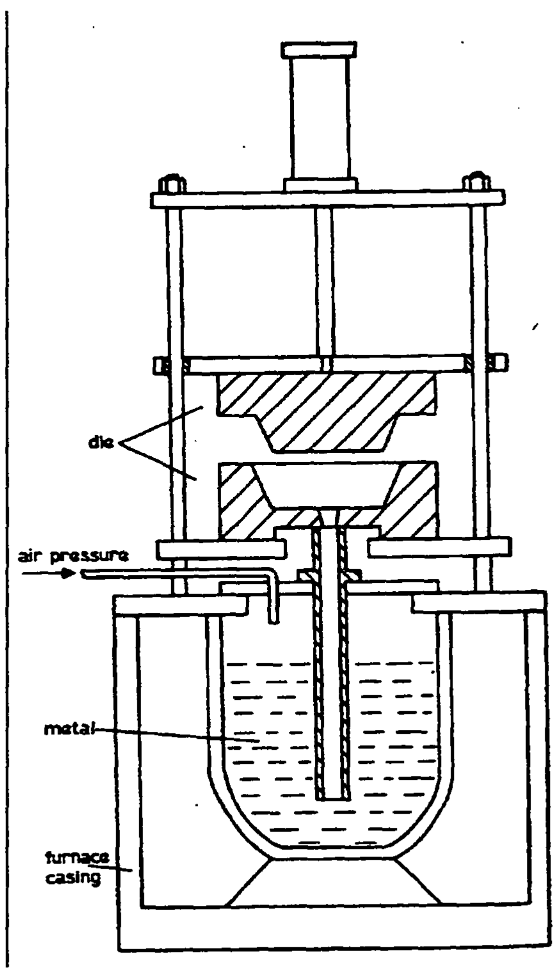


Figure 2.10 Representation of low pressure die casting.

2.5 Casting processes specific to wheels

The following table shows the take up of new technologies to the production of alloy wheels

Table 1 : Approx. breakdown of worlds commercial wheel aluminium casting processes [7] .

Casting process for wheels	**Commercial production (estimate)**
Low pressure	60 %
Gravity	35 %
Squeeze/High pressure	<5 %
Other- Semi Solid	pilot facilities only

From the above breakdown, despite the possibility of new production processes for wheels the future process improvements will be made through optimising current production processes. The focus of this thesis is to provide a means to optimise one part of the process. The process to be focused on is dimensional limitations.

A breakdown is performed to demonstrate the relative effectiveness of each process.

Table 2: Qualitative description of casting processes and their effectiveness for a number of criteria [7].

Casting process	Feeding options	Style limitations	Dimensional limitations	Die costs	Commercial success	Productivity
Low pressure	Low	Medium	Poor	Medium	High	High
Gravity	High	Good	Medium	Low-Medium	High	High
Squeeze	Low	Medium	Good	Very high	Low	very high
Semi-Solid	Good	Medium	Good	High	very low	Medium

Explanation of terms

***Feeding options*:** As previously mentioned casting of aluminium involves compensating for the difference in volume between liquid and solid aluminium. The process involved in this compensation is referred to as Feed in their are many opportunities to compensate for this the feeding options are high. For example in gravity sand castings the mouldings and the cavity are easily modified hence the feeding options are high, low pressure permanent mould die casting has large expensive dies difficult to change and because it is feed in the centre only its feeding options are low.

***Styling options*:** Refers to the limitation the stylists have for their product. For example processes involving large dies must separate. The process of separation involves cavities with draft angles, which enable separation. Some processes enable better separation characteristics than others.

Dimensional limitation: This refers to the minimal dimensions possible in the casting. Some processes involve the use of high pressure into the cavity. In high-pressure die-castings for example very thin structures such as those associated with automatic transmissions can be maintained.

Die Costs: Die costs refer to the initial capitalisation of the tooling required. Sand cast tooling can be at a low cost. High pressure/squeeze cast die pressure components are usually at a very high cost due to the necessary complexity of the dies.

Commercial Success: This refers to how industry has taken up that technology. Squeeze casting for example has enjoyed little commercial success due to the complexity of the process and some of the process restrictions, this results in a higher cost per item.

Productivity: This refers to the potential output of the process for a given time. Squeeze and high pressure die casting are fast processes, whilst

The die casting process employed at Southern Aluminium is low pressure. The following is a more detailed description of low-pressure die-casting employed at Southern follows

Inherently low-pressure die casting specifically due to the one feed point has high levels of shrinkage. The shrinkage is a result of the difference between the solid and liquid fraction. Aluminium as a solid and liquid aluminium have an 8% volume difference. This difference in volume has to be compensated for this is referred to as feed. This feeding needs to occur during the solidification process [9,10,11,8,7].

It is always the intent of design of dies at Southern to allow for this shrinkage by encouraging directional solidification. This is done in two ways:

By design, encouraging the cavity to be shaped is such a way to promote directional solidification. This can be at the compromise of weight. This can cause some limitations within the design process with respect to weight [17,12,7].

Encourage the die to set up thermal gradients, which enhance directional solidification. These main practical possibilities for doing this are cooling and die sectional alternatives ie the use of thick or thin die sections depending on the desired effect required [27, 12, 20].

How the metal is feed into the mould determine greatly, the dimensional limits. Ohtsuka et al. [12] demonstrates that one of the greatest factor influencing the solidification of die-casting is the mould coating. This paper explores more closely the thermal resistance between the mould and the coating. The paper that was written in 1982 used computer models to determine this fact. The paper demonstrates three premises, the importance of mold coat type, thickness and die temperature. He explores these variables with analysis from a computer mathematical model. Without drawing any hard or fast conclusion Ohtsuka [12] et all demonstrate the power of finite element methods that explain heat loss in die cavities with resultant shrink defects.

His work is best described by outputs showing the resultant outputs using the following devices. The issue of discussions shows the effect of coating thickness using two types of die coat and differing mold temperatures. This is represented in figure 2.12, this experimental result was confirmed using a computer model. The computer model itself is an old 2 dimensional representation but the verification data is useful for qualitative understanding.

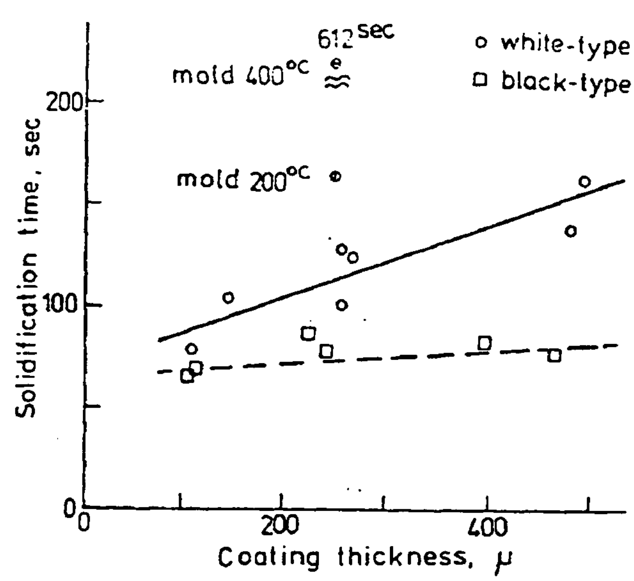


Figure 2.11: Solidification time: Ternary eutectic fin. vs. coating thickness. (Ohtsuka et al [12]).

In essence this clearly demonstrates the importance of coating thickness on the process of solidification. Whilst their is clear definition of this not being the only important variable it clearly demonstrates the importance of the variable.

Yobard [13] demonstrate the reluctance within the industry to accept computer simulation. To overcome this concern Yobard suggest the use and importance of expert systems. Expert systems take in all the available experiences. The basis of the expert system refers to DAD, this system consists of two sections, and one identifies the defect whilst other identifies methods for avoiding them.

The system is described well by the following example (for sand castings)

IF	the defect is misrun and cold shot
AND	the cause of misruns and cold shots is lack of permeability of sand
THEN	the remedy is to increase permeability of sand and venting.

This example clearly demonstrates the need for clear defect recognition with clear established methods to remedy the defect cause. Clear recognition of the defect must be given.

Another example of this is as follows.

Description of problem is:

1. Incomplete formed castings
2. Line of discontinuity
3. Rounded edges hole in the casting wall
4. Corners and edges not filled completely

These form a description for ***misrun*** and is all part of the process involved with the expert system.

The use of an expert date system has the great benefit of being able to build up a large section of experience, which has the possibility to be used and improve reactions to known and common defect. It also recognises that not any individual has the answer to some of the common problems within the foundry environment and that a central collection of knowledge using Expert systems is a fundamental use of computer technology, rather than the use of the modelling to improve a process.

Other processes that can avoid the processing of defects are the use of fluoroscopic (x-ray) penetration of the metal castings in real time. Stegeman [14] points out the advantage of real time detection of defects and the effect this is to have on a the operation to minimise defects. The feedback loop toward the casting process in Stegemans is work automated with computer technology to maximise the feedback loop to associate itself with the problem. This work showed that for a process which has a high degree of variation associated with it that individual expertise should be used and enhanced.

This work demonstrates the necessity to minimise the time from defect production to defect knowledge this same premise can be put forward to all processes that have a predecessor which has the potential to pass on any potential failures.

Jackno [15] describes the low-pressure process. This process is then an example of how the capacity of a company is used to improve the performance of the company. It shows how the process is used to produce 3 phase electric motors. This work is described by the following description:

The die is sprayed and closed. Air is introduced into the furnace body until the required pressure is reached and metal is forced via a tube into the die.
Pressure is then maintained at that level until solidification takes place. The die needs to be designed so that solidification is directional towards the sprue, which is then comparable to a riser in a gravity casting.
After solidification is complete, the pressure is released allowing the metal below the sprue in the connecting tube to fall back into the furnace crucible.
Additional cooling air or air and water mist is then applied to the die in order to increase the mechanical strength of the casting prior to ejection.
The press is then opened and ejectors operated, the casting is then extracted from the machine. The process is then repeated.

The major advantage of low pressure die casting as explained by Jackno [15] is the good casting produced in combination with automation possibilities. The disadvantage noted in this instance is low production rate in comparison with high-pressure die-casting.

Chiesa [16] has tackled the problems of die casting from a different angle. Chiesa has looked at the computation of heat losses during the filling of the mould. The conclusion from this work is interesting it. It shows that heat loss of during mould filling can be described by mathematical expression. The mathematical expression can be used to determine the heat loss for a particular section and time of metal movement. It shows that a mathematical expression can be used to determine the effective metal temperature. This is in contrast to numerical finite systems, which can be used to determine a lot of the same characteristics. The use of the work shows consistent prediction of misruns on a plate test casting when a white insulating coating was used.

Alumasac [17] Ltd looks at low-pressure die-casting from a number of fundamental characteristics, these include:

Quality - From the low pressure perspective, there is usually only one in gate, this single ingate or feeder results in lower fettling this may result in a higher quality casting. This one feeder also results in better yields, which can prove cost effective. Low-pressure die-casting makes use of higher quality die (ie tool steels) and this can relate back to the product. Low-pressure die-casting is better longer running product and is particularly suitable for weight in excess of 4.5kg.

Feeding:- Low pressure die castings can achieve thinner wall sectional thicknesses, the limitation being feeding and venting characteristics.

Economics:- In any die casting operation, costs related to tooling play an important part of the overall economics. According to Alumasc Ltd low pressure casting dies can employ loose or collapsible cores without slowing the casting process unduly. In some cases sand cores can be used, this should be avoided though

Low-pressure also permits greater scope for tool design since only a single in gate is used. The makes low pressure suitable for large flat castings.

The following comments are made for producing suitable castings:

1. Choose a suitable alloy.

2. To achieve satisfactory feeding a casting must be 1.5 mm or more. Since this must be added to the draft of the die this can become the determining factor. The die draft angle increases as the wall height diminishes. Thus for a wall depth of say, 25mm to total draft of 0.75mm represents an angel of about 2 degrees (while for a shallow wall a draft of 10 degrees may be necessary). Die draft is one of the most important factors effecting the production of distortion free castings. To obtain dimensionally accurate and distortion free castings, it is essential that the die imposes no restrictions to the stripping of the casting upon solidification. It is vital that sufficient taper is provided on any ribs in the casting to allow for rapid removal from the die without the need for undue pressure, while at the same time avoiding too large a change in section thickness at the base. As a general rule the draft should span the wall thickness of the rib at its middle height which is equal to the average wall thickness. Also the blending of walls and ribs into adjacent sections should avoid any heavy and rapid changes in section.

The institute of British foundry-men [18] investigated the issues of dimensional accuracy of low-pressure die-casting. In summary the institute looked at the following two facets:

1. The difference between the mean dimension and the drawing dimension, and

2. The spread or distributions of measured dimensions around this mean value.

The work performed found the following:

Effect of alloy: The alloy used had no significant effect on dimensional output. 4 alloys were tried (high and low silicon alloys) with no significant trend shown.

Effect of size: This was investigated with respect to wall thicknesses/weight of castings and length of castings it was found that the wall thickness had the greatest or significant effect on dimensional accuracy.
Effect of pouring temperature: This was found to have no detrimental effect on dimensional consistency, although it was discovered that heat treatment had a significant effect.
Effect of die layout: Issues such as die layout and proximity to joint lines all played no significant part to dimensional consistency required.

The overall conclusion found was that low-pressure die-casting produces dimensional accuracy similar to those found in the normal course of events or normal casting operations.

The latest developments in the casting operation have seen the use of a number of simulation packages. These include software, which take into consideration a number of Finite Element/Difference methods. These include packages such as Simulor, Magma and Pro-cast [9,20,21,22] . All the method used provide a methodology for the improvement of the casting process in response to the various parameters applied. All the computer modelling is performed with the intent to provide the means for testing and predicting potential casting defects, most particularly shrinkage.

Similar results are available when using all the stated solidification packages [19,20,21,22] , in that all these package have been able to successfully "mimic" reality and provide a means of prototype testing for many different casting conditions and types. A methodology for successful utilisation for these tools is not described.

Although attempts to understand the behavior of dimensional limitations on low pressure die casting and particularly Aluminium wheels [23-26] are not seen in the literature, they have not quantified the minimum effective thickness.

2.6 Concluding remarks

A brief introduction of various casting processes is presented. The need for reliable quantitative parameters in low pressure die casting is highlighted for minimum thickness effective casting. Some models in the literature deal with two dimensional models which are qualitative representations. It has been argued that the two dimensional analysis does not fully represent the practical case in industry. Other attempts to understand the low-pressure die casting performance as a function of various process variables have highlighted both qualitative and quantitative effects. The qualitative and quantitative trends covered are for various process variables giving a better understanding of the process. It has also been highlighted in this survey that the information such as the behavior of minimum effective thickness in casting process has been a "classified information" for many industries. Many automobile manufacturers have treated such information as "trade secrets" not available to public research. The survey identified the areas where active research in the form of simulation is currently carried out with the advent of the state of the art simulation packages. The next chapter focuses on the study of stress and solidification rate in aluminium wheel casting sections. This will be carried out as a preliminary investigation on the thin and thick sections of casting before they are experimentally verified.

CHAPTER 3

FINITE ELEMENT MODELLING

Before a comprehensive range of experimental investigation is carried out, it is appropriate to carry out finite element analysis. Finite element and finite difference methods are a means of checking qualitative and quantitative effects of performance with process variables. The quantitative reliability, however, depends on the accuracy of the constraints and the associated loading conditions. The procedure that an industry often adopts is a preliminary check to qualitatively analyze the process by finite element methods followed by a comprehensive experimental investigation to verify the models.

The common approach to resolving manufacturing issues is a quantifiable approach to a practical problem with follow up resolution of the problem. Developing dimensional limitations for low-pressure die-casting in industry, the reject rate plays an important role. For example a design for a particular wheel die has a lowest thickness to cast is at 4.5mm which resulted in an output of reject rate of 25%. Further work demonstrated a linear relationship between the thickness of this component and the reject rate. It is not uncommon with manufacturing allowances that a component will have variations. It the case of this particular component it was noted that at sizes larger than the specified amount that the reject rate was lower. This situation is unacceptable and must be the reason for the satisfactory use of the optimization tools.

Further, this leads to the general conclusion that the larger the figure the greater the likelihood of success. However, the reality is a need to achieve the lightest possible weight with the highest possibility of success. Before the Finite Element are introduced a brief review of how a product is introduced into the system at SAPL will be discussed. The current process to enable smooth introduction of product into the plant is described generically in the attached process. This is an example of concurrent engineering principles where design for manufacture and the product development evolve at the same rate.

The flow chart describes the design process in reasonable detail, which can be referred to as Advanced Product Quality Planning and Design control. This is generically referred to as the APQP process. The process shown gives all the appropriate checks and balance referred to come to the final product. The core activity within the APQP process is involvement of all areas of the plant to ensure the smooth introduction of product and processes.

Within the APQP process as mentioned there is a series of checks performed. These checks give the current effective dimensional limits. This design flow chart highlights the areas and stages where FEM methods are used in its over all structure. It can be seen from fig.3.1 that the entire design review from its inception right through to its completion comprises of 8 stages of review. Each stage comprises of a review committee that ensures the successful completion of each stage. After the request for a quote from an automobile manufacturer, SAPL begins its efforts to see the feasibility of manufacturing. In case of the aluminum wheels the front face and rear face are produced in the first instance using CAD. The second stage involves the FEA of the model. The finite element models are developed using CAD and the MAGMA SOLIDIFICATION 3d package analyses. The third stage prepares manufacturing methods and process plan for the design together with proper documentation. The rest of the stages are design reviews at various stages of production and continual development with feed back. The finite element models are continually up dated with the modified conditions from the feed back and new set of conditions are obtained.

This process is extremely efficient maintaining concurrent engineering principles of design for manufacture at all stages of review. The design stages in reviews 4-8 involves continual checking of FEM methods and how the analytical results from simulated software complement the experimental investigation. Finite element analysis studying the stress concentrations, solidification rate, impact resistance and temperature distributions are major areas of investigation for the wheels. The casting process involved in this part of the investigation is also studied using FEM techniques on a simulation package. The FEM for stress concentrations are carried out for the aluminum wheel using Patran software. The solidification analysis is carried out using finite difference methods on MAGMA 3d simulation software.

The APQP process provides the basis and the process of smooth new product. In the context of this thesis the dimensional limits are therefore defined and acted upon.

Fundamental to the APQP process is the use and implementation of the design tools. These tools includes the sophisticated packages of solidification and stress analysis, these processes will now be further defined. A brief review of finite element methods is carried out in the following section.

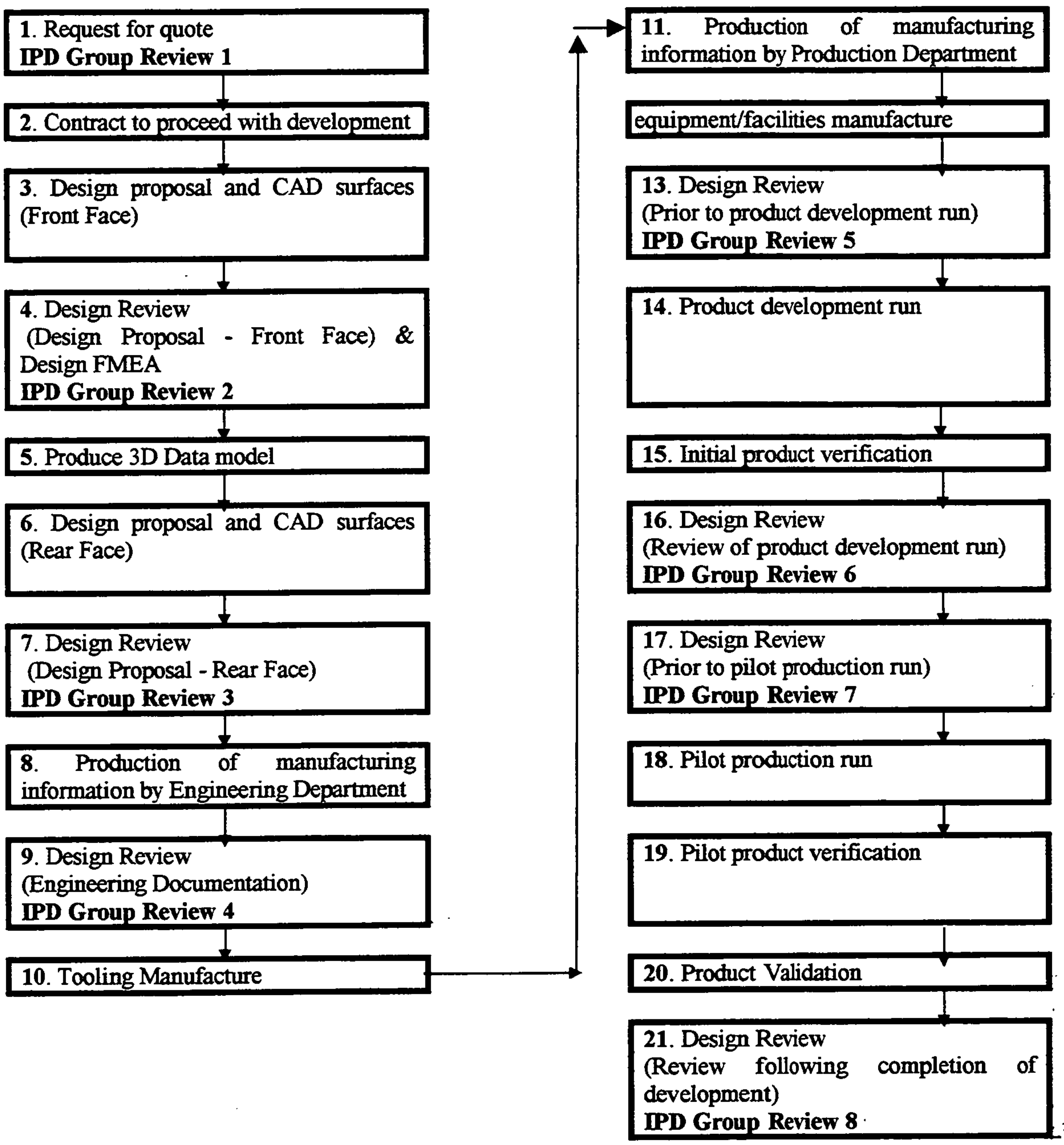


Figure 3.1 : Flow chart of the new product introduction process

3.1. Finite Element Methods

The finite element method seeks to replace a continuous type of structural problem, which can alternatively be represented by a set of partial differential equations, by a set of discrete, simultaneous linear equations readily solved by machine. The discretisation is achieved by subdividing the body being considered into a number regions and so create a set of elements and connecting nodes. The intention is purely to create regions in which the deformation will be represented by a particular algebraic function of position. The deformation within different regions (elements) will be represented by different functions, although these will be of the same general form and will normally be chosen such that displacement continuity is preserved along the element boundaries. Therefore the possibility of element separation will not arise.

On the basis of the assumed displacement function, it is possible to derive an element stiffness matrix linking element nodal 'forces' to element nodal 'displacements'. The analysis then closely follows the normal stiffness method as applied to skeletal structures in that the element stiffness matrices are used to assemble a set of stiffness equations which represent, in terms of the nodal displacements, the conditions of equilibrium of the total forces acting at the nodes with the applied nodal loads. The solution of this set of linear equations yields the nodal displacements from which the internal element forces may be determined.

3.1.1 Solution technique.

This solution is a standard technique available in standard text books [27] and the equations are not numbered since they will not be used anywhere else in this thesis. A brief and logical sequence of solution procedure is presented to cover the academic content.

1. Subdivide the structure into elements. There is a choice of shape, e.g. we may use triangles, rectangles or general quadrilaterals for a two dimensional stress case, tetrahedrons or rectangular prisms (bricks) for three dimensional cases or a ring of say triangular cross section for an axisymmetric case.

2. Define deformations of the elements by a matrix **[D]**. This is usually done in terms of deformations of the nodes of the elements (e.g. the corners of a simple triangular element). Polynomial functions are the easiest to use and they satisfy the convergence criterion which is that the deformation along the edge of one element is the same as on the contacting edge of the adjacent element.

3. Define a matrix of forces **[F]** at the nodes of the element to produce these deformations.

4. Calculate the forces in terms of the parameters defining the deformations, i.e. calculate the stiffness matrix **[K]**.

5. Observe equilibrium conditions throughout the element, i.e. form an equation of the type: **[F] = [K].[D]**.

6. Assemble the various elements together observing that equilibrium must be maintained at each node between the elements and externally applied forces/moments.

To encapsulate the above points, in order to carry out finite element analysis the following five steps must be taken.

Produce a structure that can be analyzed. or in Southern Aluminum's case a wheel must be represented in a form to enable the modeling to occur. This is usually in a "solids" CAD format, which is an electronic representation of the structure to be analyzed.

Subdivide the structure into elements of mesh. There can be a choice of shapes e.g. triangles, rectangle, tetrahedrons or rectangular prisms (bricks). At Southern Aluminium the usual choice is tetrahedrons.

Define the deformation. A matrix usually defines this. In the case of Southern Aluminium the definition of the Deformation (often referred to as **[D]**) is specific to the material used i.e. 601 aluminium alloy.

Define the forces. What are the forces placed on the article, **[F]** to produce the above deformation or vica-versa.

Analysis the results. What do the resultant forces tell us about the product what in the consequence of looking at the displayed output.

3.1.2 Element Formation (triangular element)

To illustrate the process of finite element formulation we will consider the simplest two dimensional case, that of a triangular element as shown in fig.3.2.

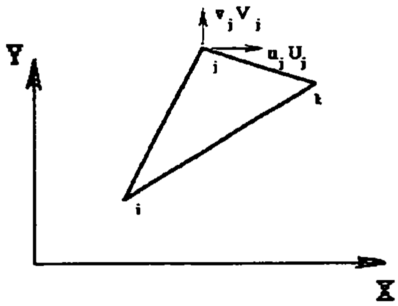


Figure 3.2 Triangular element

The simplest form of element has three nodes, i,j,k

Define displacements u_i u_j u_k in the X direction and v_i v_j and v_k in the Y direction. Also define nodal force U_i U_j U_k in the X direction and V_i V_j and V_k in the Y direction.

For the general point in the element we have displacements **u** and **v** and these need to be defined in terms of the six nodal displacements. Therefore we are limited to six coefficients in the relations between **u** and **v** and the nodal displacements.

$$\text{i.e.} \quad u = a_0 + a_1 x + a_2 y$$

$$v = b_0 + b_1 x + b_2 y$$

These equations include the effect of rigid body movement.

N.B. at i $\quad u_i = a_0 + a_1 x_i + a_2 y_i$

at j $\quad u_j = a_0 + a_1 x_j + a_2 y_j$

and at k $\quad u_k = a_0 + a_1 x_k + a_2 y_k$

We can solve these equations to find $\mathbf{a_0}$ $\mathbf{a_1}$ and $\mathbf{a_2}$ in terms of $\mathbf{u_i}$ $\mathbf{u_j}$ and $\mathbf{u_k}$.

$$\text{i.e.} \quad u = \frac{1}{2D}[\,(a_i+b_ix+c_iy)u_i + (a_j+b_jx+c_jy)u_j + (a_k+b_kx+c_ky)u_k\,]$$

where

$$a_i = x_j y_k - x_k y_j \qquad b_i = y_j - y_k \qquad \text{and} \qquad c_i = x_k - x_j$$

and the other coefficients obtained by a cyclic permutation of subscripts in the order i,j,k and

2D = twice the area of the triangle ijk

$$= \det \begin{vmatrix} 1 & x_i & y_i \\ 1 & x_j & y_j \\ 1 & x_k & y_k \end{vmatrix}$$

Similarly for vertical displacements

$$v = \frac{1}{2D}[\,(a_i+b_ix+c_iy)v_i + (a_j+b_jx+c_jy)v_j + (a_k+b_kx+c_ky)v_k\,]$$

These equations can be written in short hand form as

$$\begin{bmatrix} u \\ v \end{bmatrix} = [I N_i,\ I N_j,\ I N_k\ ][\,\delta\,]$$

where $\quad I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$

$$N_i = \frac{(a_i + b_ix + c_iy)}{2D} \qquad \text{etc.}$$

and $\quad \delta = \begin{bmatrix} u_i \\ v_i \\ u_j \\ v_j \\ u_k \\ v_k \end{bmatrix}$

To determine the relationship between nodal forces and nodal displacements we need to consider the material characteristics and loading condition.

e.g. consider a linear plane stress condition.

$$\varepsilon_x = \frac{\partial u}{\partial x} = a_1 = \frac{1}{2\Delta}(b_iu_i + b_ju_j + b_ku_k)$$

$$\varepsilon_y = \frac{\partial v}{\partial y} = b_2 = \frac{1}{2\Delta}(c_iv_i + c_jv_j + c_kv_k)$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} = a_2 + b_1 = \frac{1}{2D}(c_iu_i + b_iv_i + c_ju_j + b_jv_j + c_ku_k + b_kv_k)$$

or

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} = [\,\varepsilon\,] = \frac{1}{2\Delta}\begin{bmatrix} b_i & 0 & b_j & 0 & b_k & 0 \\ 0 & c_i & 0 & c_j & 0 & c_k \\ c_i & b_i & c_j & b_j & c_k & b_k \end{bmatrix}[\,\delta\,] = \frac{1}{2\Delta}[\,T\,][\,\delta\,]$$

N.B. ε_x ε_y and γ_{xy} are all constant within the element, thus this element is known as the plane strain element.

Material properties i.e. Hooke's law

$$\sigma_x = \frac{E}{1-\upsilon^2}\,[\,\varepsilon_x + \nu\,\varepsilon_y\,]$$

$$\sigma_y = \frac{E}{1-\upsilon^2}\,[\,\varepsilon_y + \nu\,\varepsilon_x\,]$$

$$\tau_{xy} = \frac{E}{2(1+\upsilon)}\,\gamma_{xy}$$

or $$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix}\sigma_x = \frac{E}{1-\upsilon^2}\begin{bmatrix}1 & \nu & 0\\ \nu & 1 & 0\\ 0 & 0 & \frac{1-\nu}{2}\end{bmatrix}\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{bmatrix}$$

or $$[\sigma] = \frac{E}{1-\upsilon^2}\,[\,D\,][\,\varepsilon\,] = \frac{E}{2\Delta(1-\upsilon^2)}\,[\,D\,][\,T\,][\,\delta\,]$$

Strain Energy.

$$V = \int_V \left[\int_0^{\varepsilon x}\sigma_x d\varepsilon_x + \int_0^{\varepsilon y}\sigma_y d\varepsilon_y + \int_0^{\gamma xy}\tau_{xy} d\gamma_{xy}\right] dV - \sum_1^6 \int_0^{Si} F_i dS_i$$

where S_i $= u_i, u_j, u_k, v_i, v_j, v_k$ in turn.

For an element of uniform thickness $dV = t\,dA$

$$\therefore \frac{\partial V}{\partial S_i} = 0 = t\int_A \left[\sigma_x \frac{\partial \varepsilon_x}{\partial S_i} + \sigma_y \frac{\partial \varepsilon_y}{\partial S_i} + \tau_{xy}\frac{\gamma_{xy}}{\partial S_i}\right] dA - F_i$$

Since stress and strain are constant over the element we have:-

$$F_i = \Delta t\,\{\,\sigma_x \frac{\partial \varepsilon_x}{\partial S_i} + \sigma_y \frac{\partial \varepsilon_y}{\partial S_i} + \tau_{xy}\frac{\partial \gamma_{xy}}{\partial S_i}\,\}$$

Now

$$\frac{\partial \varepsilon_x}{\partial u_i;\ \partial u_j; \partial u_k} = \frac{b_i}{2\Delta};\ \frac{b_j}{2\Delta};\ \frac{b_k}{2\Delta}$$

$$\frac{\partial \varepsilon_x}{\partial v_i;\ \partial v_j;\ \partial v_k} = 0\ ;\ 0\ ;\ 0$$

$$\frac{\partial \varepsilon_y}{\partial u_i;\ \partial u_j;\ \partial u_k} = 0\ ;\ 0\ ;\ 0$$

$$\frac{\partial \varepsilon_y}{\partial v_i;\ \partial v_j;\ \partial v_k} = \frac{c_i}{2\Delta};\ \frac{c_j}{2\Delta};\ \frac{c_k}{2\Delta}$$

$$\frac{\partial \gamma_{xy}}{\partial u_i;\ \partial u_j;\ \partial u_k;\ \partial v_i;\ \partial v_j;\ \partial v_k} = \frac{c_i}{2\Delta};\frac{c_j}{2\Delta};\frac{c_k}{2\Delta};\frac{b_i}{2\Delta};\frac{b_j}{2\Delta};\frac{b_k}{2\Delta}$$

$$\therefore \quad \begin{bmatrix} U_i \\ V_i \\ U_j \\ V_j \\ U_k \\ V_k \end{bmatrix} = \frac{\Delta t}{2\Delta} \begin{bmatrix} b_i & 0 & c_i \\ 0 & c_i & b_i \\ b_j & 0 & c_j \\ 0 & c_j & b_j \\ b_k & 0 & c_k \\ 0 & c_k & b_k \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix}$$

or
$$[U] = \frac{t}{2} [T]^T [\sigma]$$

$$= \frac{Et}{4\Delta(1-\upsilon^2)} [T]^T [D][T][\delta]$$

Plane strain

The only difference between plane stress and plane strain is in the [D] matrix i.e. in the relations between stress and strain. In plane strain we have some value of s_z

$$\therefore \quad \varepsilon_x = \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} - \nu \frac{\sigma_z}{E}$$

$$\varepsilon_y = -\nu \frac{\sigma_x}{E} + \frac{\sigma_y}{E} - \nu \frac{\sigma_z}{E}$$

$$\gamma_{xy} = \frac{2(1+\upsilon)\tau_{xy}}{E}$$

But also $\varepsilon_z = 0 = -\nu \frac{\sigma_x}{E} - \nu \frac{\sigma_y}{E} + \frac{\sigma_z}{E}$

And on eliminating σ_z we find:-

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} \sigma_x = \frac{E(1-\upsilon)}{(1+\upsilon)(1-2\upsilon)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & 0 \\ \frac{\nu}{1-\nu} & 1 & 0 \\ 0 & 0 & \frac{1-2\nu}{2(1-\nu)} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}$$

3.1.3 Limitations of the simple Element

Over the area of the element the strain is constant but will change from element to element. Thus there is an apparent abrupt change in strain at the boundary, even though both elements displace the same amount along the boundary. To overcome this problem we can add additional nodes to the element as shown in fig.3.3.

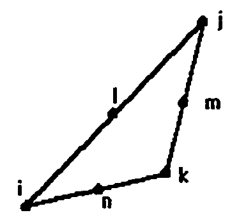


Figure 3.3. Additional Nodes Added to Element.

l,m and n are points along the sides of the element, not necessarily the mid points. Thus the displacements are given in terms of 6 values.

i.e. $u = a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2$

The displacement function is parabolic along the sides of the element and is uniquely specified by the displacements at i,j and k. Thus the adjoining element has the same boundary displacements. Strains and stresses take on a linear variation across the element. This element is commonly referred to as isoparametric.

Another common element is a rectangle as shown in fig.3.4. This element offers an extra nodal value allowing better conformity than the simple triangular element.

$$\mathbf{u} = \mathbf{a_0 + a_1x + a_2y + a_3xy}$$

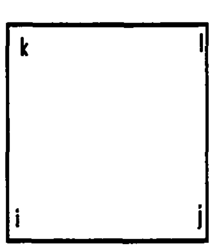


Figure 3.4 Rectangle Element

The following section deals with the solution technique using the Patran software.

3.2 Solution Using PATRAN

PATRAN is a finite element package designed for use on personal computers. It has a limited array of available element types because of the size limitations of PC.'s. However there is a sufficient range of elements to make it a useful tool for general engineering stress analysis applications.

Available elements:

1. Beam elements. Used for structural frames.
2. Constant strain triangular elements (CST). The simplest two dimensional element. Strand6.1 requires elements to be entered either as quadrilaterals or triangles but treats each quadrilateral element as four triangles. Elements can be either plane stress or plane strain and can include bending, i.e. it can be used to calculate out of plane deformations in plates. Triangles are obtained by collapsing one side of a quadrilateral.
3. Linear quadrilateral element. This form of element has a slightly better form of defining polynomial. Four nodes define the element.
4. Shell element. A special element for shells. Element has both membrane and bending effects.
5. Isoparametric plate element (8 node element). This element allows for curved boundaries within the element and because of the better definition within the element fewer elements are needed for the analysis.
6. Axisymmetric elements. For the special three dimensional case with axial symmetry, elements corresponding with CST's or linear quad's can be used but specified as axisymmetric.
7. TETR4 element. This element is a tetrahedral shape with a node at each apex. It is similar in nature to a CST element in that the describing polynomial is linear. Therefore strains are constant.
8. TETR10 element. A tetrahedral element with nodes at the midpoints of each edge. i.e. it is parametric.
9. WEDG6 element. A three dimensional wedge shaped element with nodes at each corner. Again similar to the CST element with constant strains.

10. WEDG15 element. A wedge shaped element with nodes at the midpoints of the edges. i.e. parametric.

11. BRIK8 element. A general three dimensional element with nodes at each corner only. Again similar to the CST element with constant strains.

12. BRIK20 element. A general three dimensional parametric element with nodes at the mid points of each edge.

13. BRIK16 element. A general three dimensional brick element with parametric formulation in opposite faces but linear formulation connecting those faces. This element is useful for thin structures, i.e. plate bending conditions.

The package allows both isotropic and orthotropic materials as well as laminated composites. It can handle thermal effects and inertia as well as surface pressures, edge stresses and nodal loads. Since it essentially solves non-dimensional equations any set of units are satisfactory provided the entire set is consistent. The package will also allow the solution of heat and fluid flow problems. Non-linear effects, both material non-linearities and geometric non-linearities can be accommodated though the iterative nature of the solutions can be prohibitively long.

3.2.1 Data Input and Solution.

PATRAN has two editors available for data entry. One of these is referred to as the "Online Editor" where data is entered directly from the keyboard. The other is known as the "Graphical editor" with interaction between operator and an image of the structure being generated. Since this second editor is the easier to operate it will be the only one considered in these notes.

Data input can be considered in several well-defined steps.

1. Node input. Locate nodes within the structure. Use symmetry where possible to reduce the size of the structure being analyzed.

2. Element input. Connect nodes to form elements. Use can be made of repetition. E.g. subdividing element or repeating elements.

3. Freedoms. Input conditions on nodes. Fixed or free to move with three translations and three rotations.

4. Load input. Forces and moments.

5. Node constraints. Allows specific deformations on nodes, e.g. uniform deflection over several nodes.

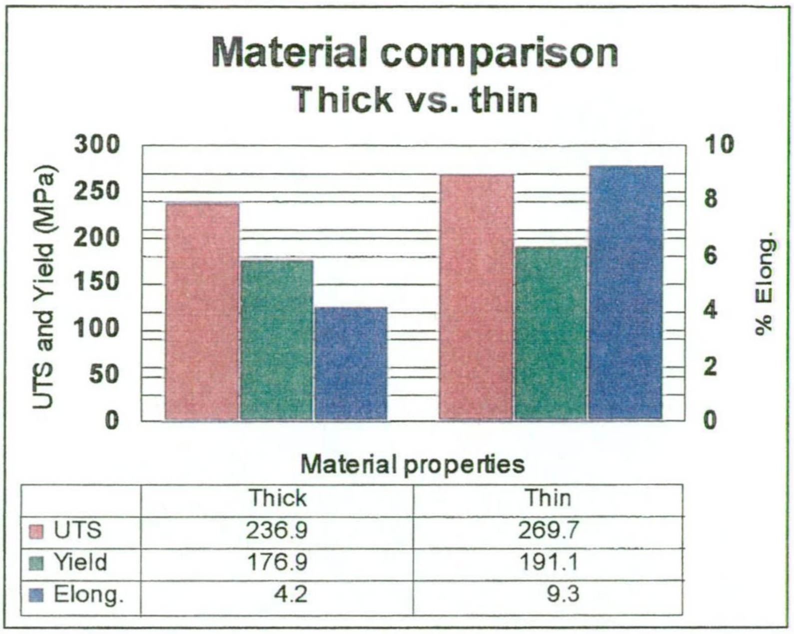
After creating mesh for the desired object. The solution is obtained using the "Solvers" from the main menu.

Select "Solvers" from the main menu and then select the type of solution from the list. N.B, "Transient Dynamics" and "Harmonic Response" can not be conducted without first solving for the natural frequencies. A linear buckling solution can not be conducted without firstly solving the "Linear Static" problem. This aspect is common for most of the finite element packages available in the market.

After the solution has been successfully completed the frames highlighting the stress concentrations in the wheel can be sent out to printers as output. The output of FEA shows the behavior of the piece under consideration that has gone through internal stress changes due to external forces. The stress analysis performed on wheels has its output as two major functions:

1. **Shows a stress distribution:** Are the stress evenly distributed or is their a clue as to how to more evenly the design of the product may distribute these stresses.
2. **Gives and absolute stress value:** Is the stress value indicated greater than a historically achievable figure. An aluminum casting is not an isotropic material due to the differing solidification patterns of the casting, this point is further discussed below. This property of the material tends to make the acceptable stresses within the material lower than those figures normally published. This must be considered when analyzing the results.

The point of significance within the within the above point is important due to the normal inconsistency of the material properties on a low-pressure cast wheel. This inconsistency can be demonstrated various ways. Figure 3.5 shows an example of the mechanical properties of a thick and thin section of the wheel. It shows a significant difference in the properties of the wheel despite the wheel consisting of the same initial material i.e. cast aluminium 601. The reason for this is solidification time related. An area that is solidified quickly has minimal defects, as in a thin section. If the solidification time is long, as in a thick section, there is a higher likelihood of failure due to the presence of casting defects. The existence and control of these casting defects is a matter that has been under a large degree of investigation from many sources. This issue will not be discussed within the context of this thesis but it should be noted.



	Thick	Thin
UTS	236.9	269.7
Yield	176.9	191.1
Elong.	4.2	9.3

Figure 3.5. Material homogeneity, source Southern Aluminium material data base

A brief explanation of the above mechanical terms of UTS, Yield and Elongation is appropriate.

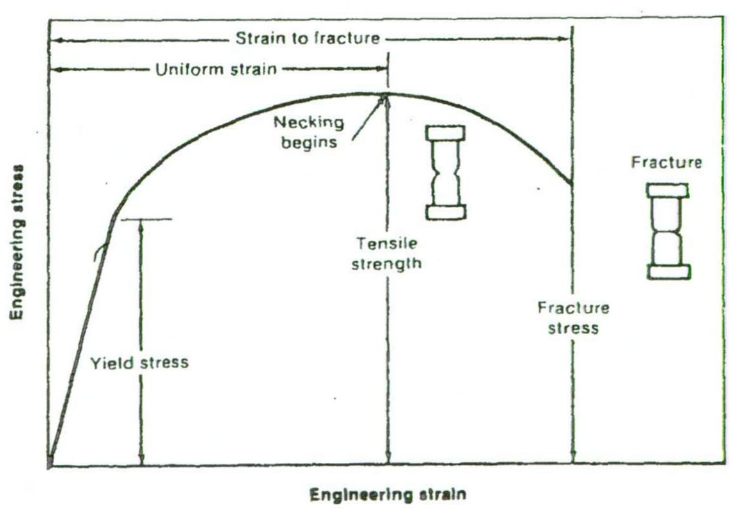


Figure 3.5 Typical "Engineering" stress strain curve.

From the typical stress strain curve shown in fig.3.6 the following critical three features are discussed

Firstly, the "yield stress" line can be also referred as the elastic region. In general the material behaves in a linear fashion. The point at which the material no longer behaves in a elastic manner is deemed the Yield point. The slope of the line is often referred to as Young's Modulus. This is a material property, and only applies within the elastic region when stress and strain are directly proportional. Within the current FEA packages this linear relationship is assumed until break. This is why the absolute stress values used in context with the FEA packages significantly exceed those values achieved. Secondly, the highest stress the material will withstand prior to breakage is deemed the Ultimate Tensile Strength (UTS). And finally, the critical feature is deemed elongation, which refers to the ultimate strain at failure.

Fig 3.5 clearly demonstrates the superior properties of the "thin" section material, in all engineering measures the material in the thinner (faster solidified sections) in superior. This issue must be taken into consideration during the analysis of the FEA results and will be discussed in the 4th chapter.

As discussed the FEA stress analysis used assumes a linear stress-strain relationship. It does not recognize that the material used for wheel manufacture only behaves in with a linear stress strain relationship during the elastic period, for these reasons the following assumptions need to be made in analyzing the output.

1. **For Impact loading**. The failure mode for impact loading is fracture. Fracture occurs if the materials UTS and subsequently elongation properties are exceeded. Extrapolation of a "normal" stress strain curve indicates that failure will occur at approximately 5% (dependent on the position in the casting) elongation. Normal FEA analysis assumes "straight line" stress strain curves. This is an incorrect approximation since like material Aluminium 601 has an elastic, yield and plastic region. This equates to approx. 800 MPa, and subsequently this is the figure used determine the success or otherwise of the design.

2. **For Bending Fatigue**: It is unlikely that fatigue will result if the yield value is not exceeded. For this reason the criteria for success or failure in rotary bending is a value closer to 150 MPa.

As with all aids to the manufacturing process FEA is a tool for minimizing potential failures. It should be noted that in many instances the tools used do not reflect reality.

An example of note within FEA is the effect for example of surface peening. Surface effects at current levels of meshing and calculation cannot necessarily be determined. These can currently only be determined by quantifiable results. This level of refinement is possible one of the next stages of development of FEA stress analysis.

It is important to note that for any design of aluminum wheels or any engineering object, it is essential to cater for the following two issues:

1. **Ensure that the stress is distributed as evenly as possible.**

2. **Ensure that the maximum stress loading does not exceed a pre-determined or historically excessive amount.**

3.3 Use of FEA (stress analysis) at Southern Aluminium.

As mentioned above the stress analysis is carried out at Southern Aluminium using at Patran solver incorporated with the Uni-graphics GFEM package which is commercially available. This original package came from the MacDonald Douglas Co-operation. This commercially available package with associated Uni-graphics equipment is extremely accurate with in-built solution method outlined above.

Stress analysis for the automotive wheel industry must be completed using three-dimensional analysis. The finite element method[3] used for wheel analysis seeks to replace a wheel into a continuous structural problem, which can alternately be represented by a set of partial differential equations, by a set of discrete, simultaneous linear equations readily solved by a computer. A brief outline of solution procedure is presented above. The discretion is achieved by subdividing the body being considered into a number of regions and so creates a set of elements and connecting nodes. The intention is purely to create regions in which the deformation will be assumed to be represented by a particular algebraic function of position. The deformation within different regions (elements) will be represented by different functions, although these will be of the same general form and will normally be chosen such that displacement continuity is preserved along element boundaries. Therefore the possibility of element separation will not arise.

On the basis of the assumed displacement function, it is possible to derive an element stiffness matrix linking element nodal "forces" to element nodal "displacements". The analysis closely follows the normal stiffness method as applied to skeletal structures. The element stiffness matrices are then used to assemble a set of stiffness equations, which represent, in terms of nodal displacements, the conditions of equilibrium of the total forces acting at the nodes with the applied nodal loads. The solution to this set of linear equations yield the nodal displacements from which internal forces may be determined.

A typical finite element mesh for an aluminum wheel is shown in fig.3.7. It can be seen that the three dimensional structure that has been developed using a significantly large number of nodes and bricks. A finer mesh ensures a reliable qualitative analysis and care is taken at all stages during the mesh development to improve qualitative accuracy.

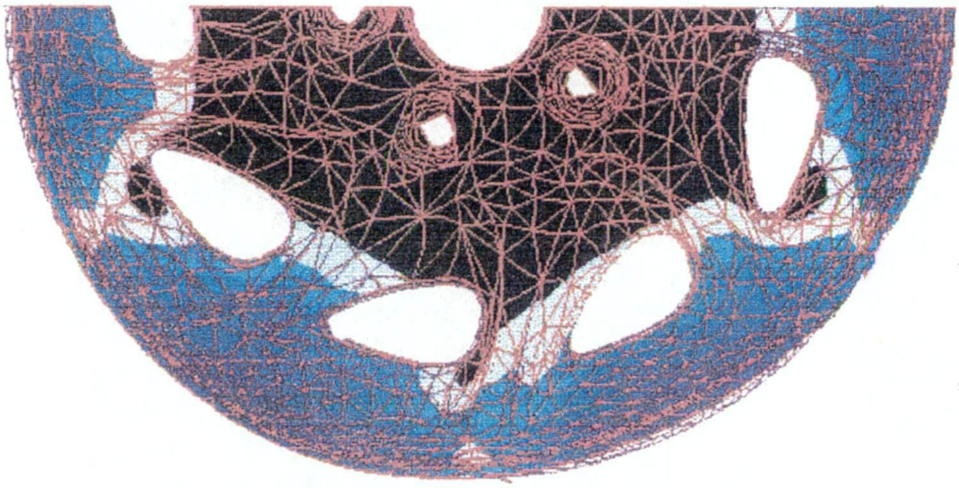


Figure 3.7 Typical aluminium wheel mesh.

At Southern Aluminium the loads that must be applied to a wheel are dynamic. The critical structural criteria that must be met are:

1. **Impact Loading:** The wheel must perform a simulated curb impact test. This test is carried out by dynamically hitting the wheel with a specific weight. The impact weight may change depending on the specifications required of it. Within the FEA stress analysis due to constraints within the FEA packages the best-simulated load can only be static. The static load used is 1.5 times the dynamic load. This condition best approximates the effect of the dynamic load. Fig 3.8 represents the equipment used at Southern Aluminium to perform the impact simulation. As can be seen the impact equipment used has 2 fundamental elements. The first being the variation that can occur to weight depending on the severity of the test i.e. a heavier car, and the fact the stand for the weight has a degree if "give". The intent of this is to approximate a vehicle suspension, which is not a solid body.

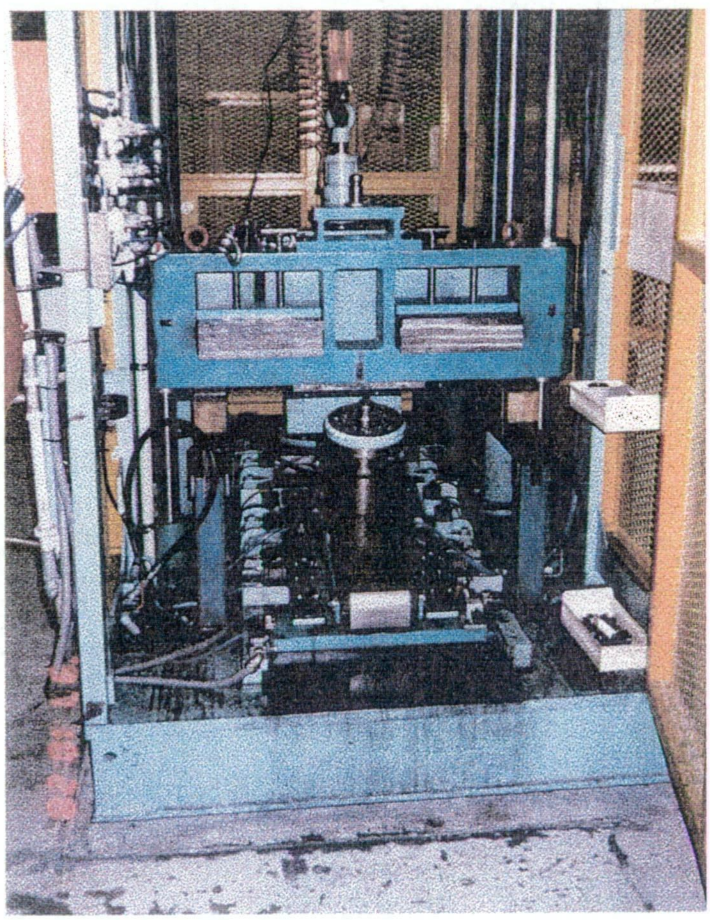


Figure 3.8: Photograph of impact machine used to simulate curb impact.

Fig.3.9 represents the initial impact FEA analysis of a new ford wheel developed at SAPL. It can be clearly seen of figure 3.9, the high stress areas and the stress distribution. In particular a high stress area is noted in the window area (in red) of the wheel. The absolute value (848 MPa) achieved in this area exceeds the previously stipulated maximum value of 800 MPa. A further consideration is that the area shown to exhibit high stress can easily be deemed as a thin section. As previously discussed thin sections exhibit better mechanical properties. This is one of the elements that must be considered within the context of stress analysis. Apart from this specific area of concern the FEA analysis developed shows little area of concerns with no specifically high stress areas and fairly evenly distributed stress. It is also worth noting that the FEA outputs will often develop very high levels of localized stress. These are often mesh related and the final analysis needs to consider the effect of this phenomena. A further FEA analysis is later demonstrated which shows the effect of product design changes. The change included the use of ribs in the center of the product. The effect of this rib clearly demonstrated the effect on the previously noted high stress area and subsequent lowering of absolute stress.

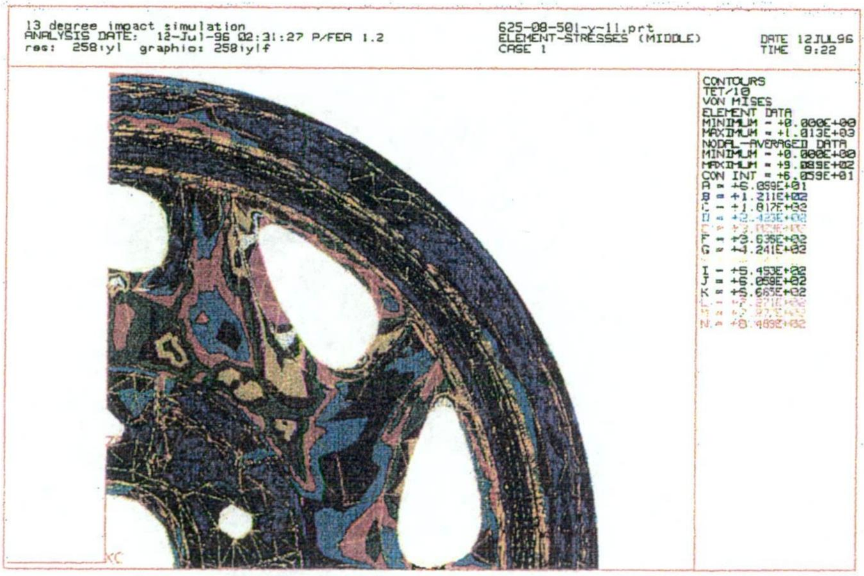


Figure 3.9 represent the initial impact FEA analysis of a new Ford wheel developed at Southern Aluminium.

The next stage of finite element testing involves checking the wheel for fatigue testing. A test routinely performed by major automobile and ship manufacturers on most of their parts for cyclic stress resistance. The criterion simulated is rotary bending. Rotary bending fatigue is simulated cornering fatigue. The procedure, in this case, is carried out by restraining the hub of the wheel (as it would be in a vehicle) and restraining the rim. The wheel is then rotated with a specific load place on the hub. This produces a moment that will result in accelerated fatigue. This dynamic test is simulated in FEA analysis by static loading as has been for the stress analysis above. The hub is restrained (as setup condition within the program) and a static load is place along the line of restraint. Since the analysis is limited to only a portion of the wheel it is important the right sections are analyzed. Figure 3.10 shows the rotary bending fatigue rig used to perform cornering fatigue tests.

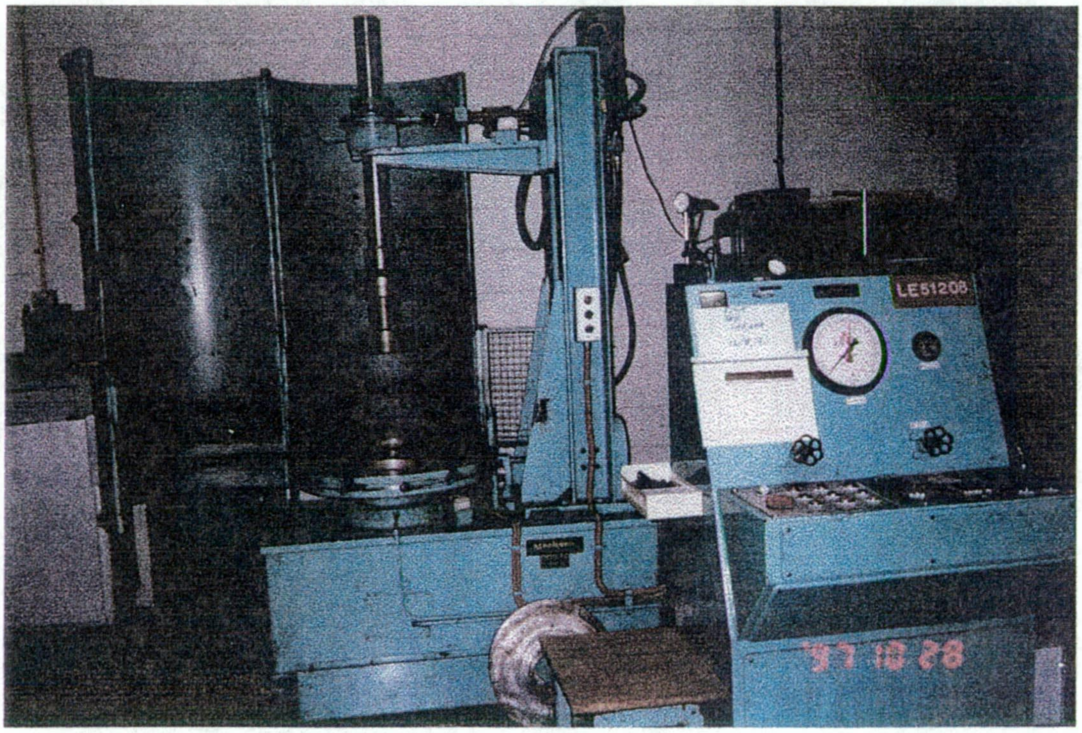


Figure 3.10: Photographic representation of the rotary bending fatigue rig used to perform cornering fatigue.

The simulated FEA of the above test procedure fig 3.10, is shown in figure 3.11

The stress in fig 3.11 represent the stress applied during the rotary bending fatigue. It can also be seen that the high stress area, demonstrated in the same area as for impact loading. That is the high stress area is adjacent to the window area. This complements the findings of the impact analysis.

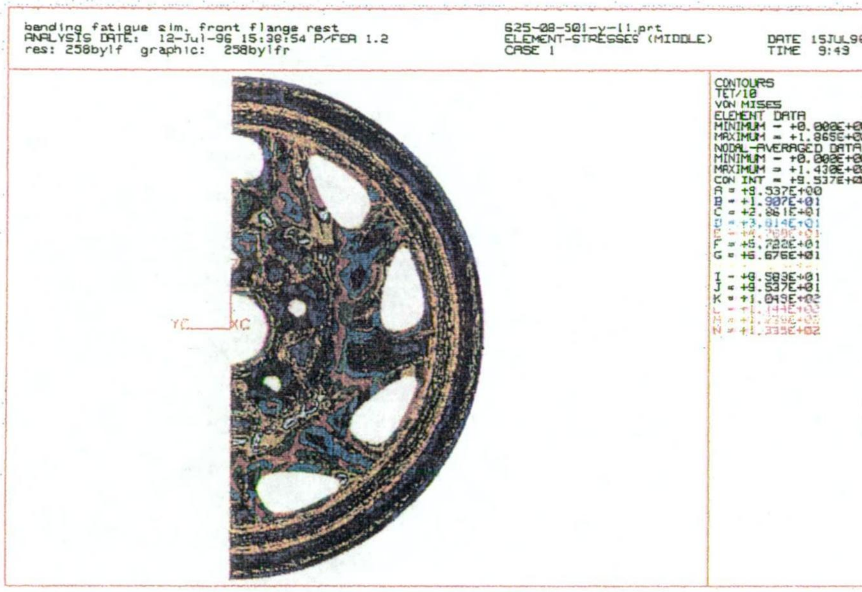


Figure 3.11: Finite Element analysis for rotary bending fatigue of a recently developed product.

The above process has highlighted that finite element methods, associated computer software and procedures used on aluminum wheels for stress and fatigue analysis. The following section deals with the solidification analysis. From low-pressure die-casting point of view, the rate of solidification and direction of solidification of an aluminum wheel is extremely important. The rate at which different sections of the wheel solidify and the retention time with in the die are extremely important for error free casting.

It is important to note that the solidification analysis like any other fluid dynamic analysis uses finite difference method instead of finite element method. Finite Element Analysis of a wheel is a finite element mesh of the wheel only, while Magma and Finite Difference Method represents the wheel and the die. With computational restrictions and Magma solidification requiring large modeling sections the added cost of improved computational facilities was never deemed to be worthwhile. FEA of the wheel more closely approximates the wheel due to better mesh densities and shape approximates of the wheel. It therefore requires higher computational ability. This is one of the reasons why for Magma solidification Southern Aluminium has remained with the FDM approach.

A brief description of Magma Solidification simulation package is carried out in the following section:

3.4 The use of MAGMA Solidification.

Magma is a 3D-solidification package used to simulate the casting process. Magma, which is a propriety product, has ability to do solidification analysis by both finite difference and finite element methods. Due to normal practice and practical computation issues. Magma within this thesis and the Southern Aluminium operation was used as a finite difference package.

Finite difference within the Magma process replaces differential equations by a number of linear simultaneous. In practice this leads to the analyzed shape being made up of a number "blocks" which provide the approximation of reality. In the case of Southern Aluminium these blocks for the product are cubes of 3 mm. Limited computing power and historical precedent is the reason for this. It is always worth noting that the accuracy, particularly for small inconsistencies must be analyzed in context to the block size shown.

As the mesh constructed of the 3D article is made up of a large number of "cubes" the mathematics is essentially similar to that of the finite element method and are not difficult to converge a solution that realistically approximates. Verification of the output is primarily involves the checking of the predicted outputs with those in practice. Occasionally thermocouple verification proceeds but this can lead to inconsistencies due to the inherent difficulties associated in using thermocouples. This will be discussed after the solidification analysis is carried out.

The process Southern Aluminium employed to enable Magma solidification to take place is the following:

1. All die components where constructed/modeled in a CAD package, in the case of Southern Aluminium this was the commercially available Unigraphics product. Die components include, top and bottom cores side cores and frames. All cooling pipe slots and locations were also modeled.
2. The wheel cast surfaces were also constructed in a similar fashion. This includes rear and front surfaces. The wheel cast surfaces are obviously part of the die surfaces.
3. The available information was then converted into a CAD file format referred to as a SLA file. This is a method of converting the available CAD file, which is a series of surfaces, into a triangulation format, which is recognized within the Magma environment.
4. The exported CAD files are then combined with the Magma process to provide a completed die assembly.
5. The completed Magma file then proceeds through an Auto-mesh process which then enables the package to be set up for and then complete its modeling cycle.
6. All variables such as cooling, die temperatures, pressurization, and cycle times must be imputed to begin the modeling process.

Magma as a solidification package, which uses basic heat transfer calculations to enable the modeling to take place. The basis of all the heat transfer calculation is as calculated using the heat transfer co-efficient or a contact resistance term, this can be represented in the following manner.

$$\left\{ \frac{L}{K} + \frac{1}{h} + \frac{1}{t} \right\} = R_{TC}$$

Where L and K are distance and temperature terms both in the metal (cavity) and the die whilst the inverse h term refers to the interface term. The basis of Magma is the successful commercial use of standard heat transfer calculations.

The output of Magma is used in a systematic manner. Magma is analyzed via various means. It is then not uncommon in the Southern Aluminium to perform, what is referred to as a DOE (Design of Experiment) or more correctly a Plackett-Burman screening design. A DOE is a scientific method of minimizing the amount of experiments required while maximizing the effect of variable examination of the experiment. A typical example of a DOE experiment is shown below. The example given is a 7 variable in 8 run and within the Southern Aluminum context is referred to as the standard DOE since its is a design of experiment capable of running easily within the context of the SAPL operation. The methodology behind the DOE is described.

In 1946, R. L. Plackett and J.P. Burman published an article that defined a class of factorial designs based on mutually orthogonal sets of contrast. While they are now more commonly called "screening designs" since they provide an effective way to consider a large number of factors with a minimum number of observations. By using these designs, one can quickly separate inert factors from active factors, allowing most of the research effort to be concentrated on the active factors

As a class, the Plackett-Burman designs have several characteristics. Among these are:

(1) The factors in a particular design will all have L levels, where L must be a prime number greater than 1, e.g. L=2,3,5,7,11 etc.
(2) The number of run (treatment combinations) for a particular design must be a multiple of L^2. Thus, if a design involves factors at two levels, it will have a number of runs that is equal to some multiple of 4, while a design that involves factors at three levels will have a number of runs that is equal to some multiple of 9.
(3) All main factor effects are estimated with the same precision. This means that one does not have to anticipate which factors are the most the likely to be important when setting up the study.
(4) Because of the orthogonal contrasts, all main factors are estimated independently of each other. While iterations may contaminate the estimates of the main effects, at least the main effects do not contaminate each other.

The "generic" design used is given below:

Table 3.1: Generic 8 variable and 7 run DOE used for plant optimization processes.

Variable Run	**A**	**B**	**C**	**D**	**E**	**F**	**G**
1	-	-	-	-	-	-	+
2	-	-	+	-	+	+	-
3	-	+	-	+	-	+	-
4	-	+	+	+	+	-	+
5	+	-	-	+	+	-	-
6	+	-	+	+	-	+	+
7	+	+	-	-	+	+	+
8	+	+	+	-	-	-	-

The alpha figures shown in Table 1 are in reference to the variable i.e. A may be the variable of spoke cooling on time where A- is no spoke cooling and A+ refers to high spoke cooling. In order to understand the process the following DOE example is represented using the above design.

The following design of experiment is typically used with the Magma solidification process.

Table 3.2: A typical DOE used to optimize the cooling process.

Variable	Variable name (cooling pipes)	Low Level (-)	High Level(+)
A	Spoke on time	20	120
B	Spoke wait time	20	120
C	Rim on time	10	150
D	Rim wait time	10	150
E	Hub ring	off	50/150
F	Disk	off	30/250
G	Hub droppers	off	60/240

Note: The above able refers to a number of critical cooling channels used in the manufacturing of low-pressure die cast wheels. Spoke on time refers to the time a cooling channel located near the spoke on a low pressure casting will be on for, wait time refers to the length of time the cooling channel will not be used prior to it being turned on within the cycle. Rim, Hub and Hub ring all refer to cooling locations relative to the product, the use of off rather than a specific timing is used to provide economy in experimental design.

Using the above experimental design the variables could then be placed within a design matrix. Table 3 indicates how the experiments were completed.

Table 3.3: Experimental run as described by Plackett-Burman, taking into consideration typical Southern Aluminium variables.

Experiment No.	Spoke on time	Spoke wait time	Rim on time	Rim wait time	Hub ring	Disk	Hub Droppers
1	20	20	10	10	Off	Off	60/240
2	20	20	150	10	50/150	30/250	Off
3	20	120	10	150	Off	30/250	Off
4	20	120	150	150	50/150	Off	60/240
5	120	20	10	150	50/150	Off	Off
6	120	20	150	150	Off	30/250	60/240
7	120	120	10	10	50/150	30/250	60/240
8	120	120	150	10	Off	Off	Off

Each of these experiments was run according to the DOE to establish the process possibilities within the product. The experiment above was then put through a process of assigning values of the experiment to three critical operating parameters these were:

1. **Directional Solidification:** This refers to the gradient set up within the process, though difficult to quantify the result are judged according to certain criteria an example of a "good" thermal gradient is shown. The thermal gradient is judged and the result is given figure between 1 and 10. This can be clearly demonstrated by the following examples. The majority of casting defects occur if directional solidification of the material is not allowed to occur. Directional solidification is a requirement of solidify aluminium since the volume difference between solid and liquid aluminium is 8%. If the material deficit upon solidification cannot be made up by liquid metal a void must result. This is most likely **not** to occur if the temperatures setup within the process change as a defined sequential thermal gradient. This is why it is important good thermal gradients must achieved in the development stage. Figure 3.12 demonstrates an example of an exceptionally

good temperature gradient. If the gradient is poor as demonstrated in figure 3.13 the likelihood of poor manufacturing performance is likely, and one of two things must occur, either the product or process is modified. The examples given below are identical product with process changes only.

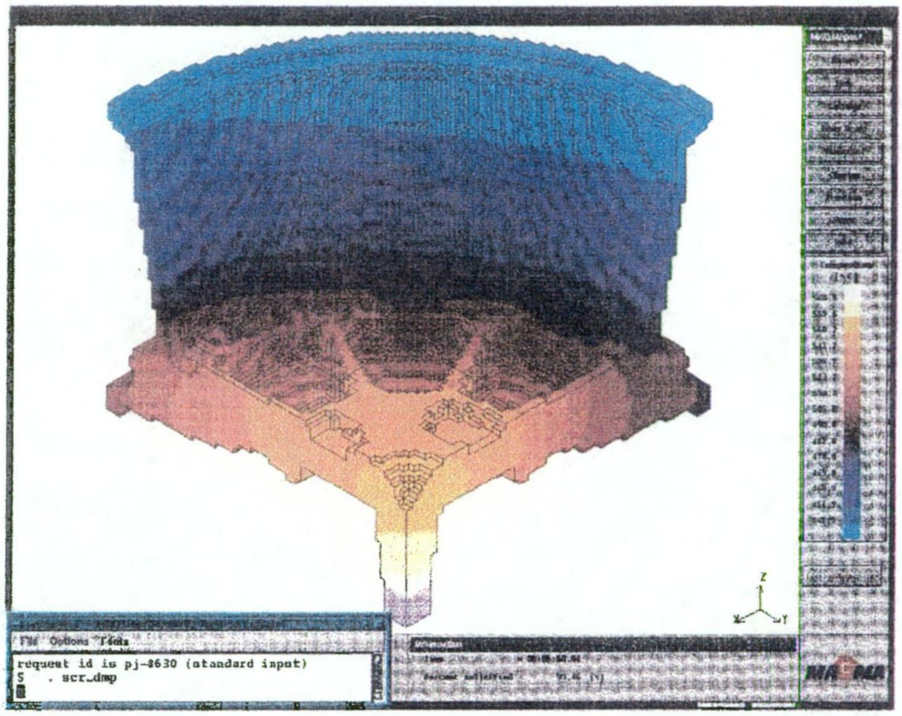


Figure 3.12: A thermal Magma output showing a "good" thermal gradient

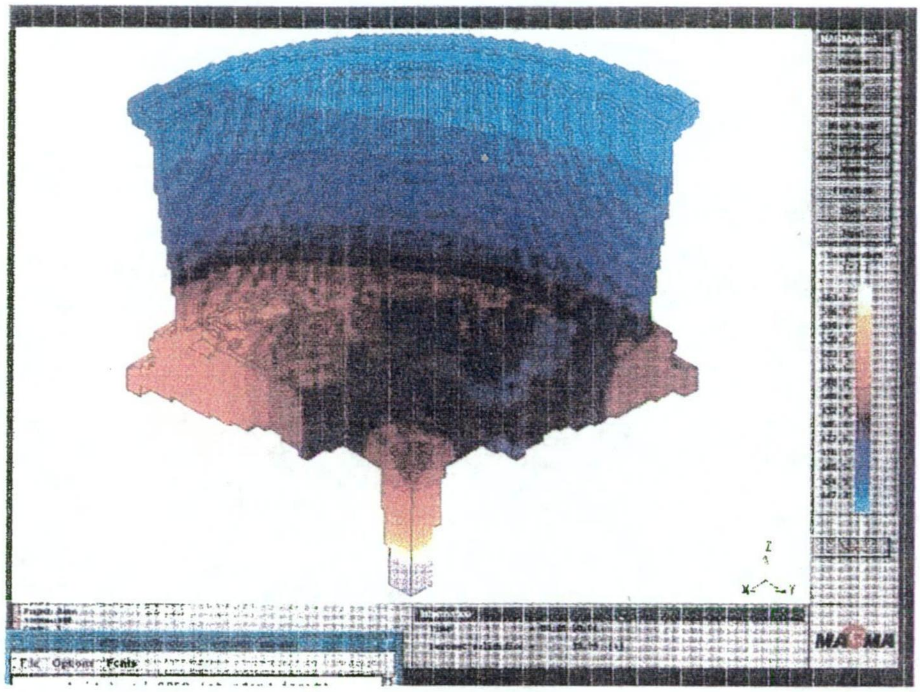


Figure 3.13: A thermal Magma output showing a "bad" thermal gradient

2. **Porosity:** Magma provides an output based on porosity prediction. The output is control volume free space dependent, an example of this is shown in fig.3.14. It is normal for good thermal gradient wheels to exhibit a low porosity prediction. The measures of thermal gradient and porosity prediction are similar but the outputs shown are also used due to the quantifiable result that is given i.e. the severity.

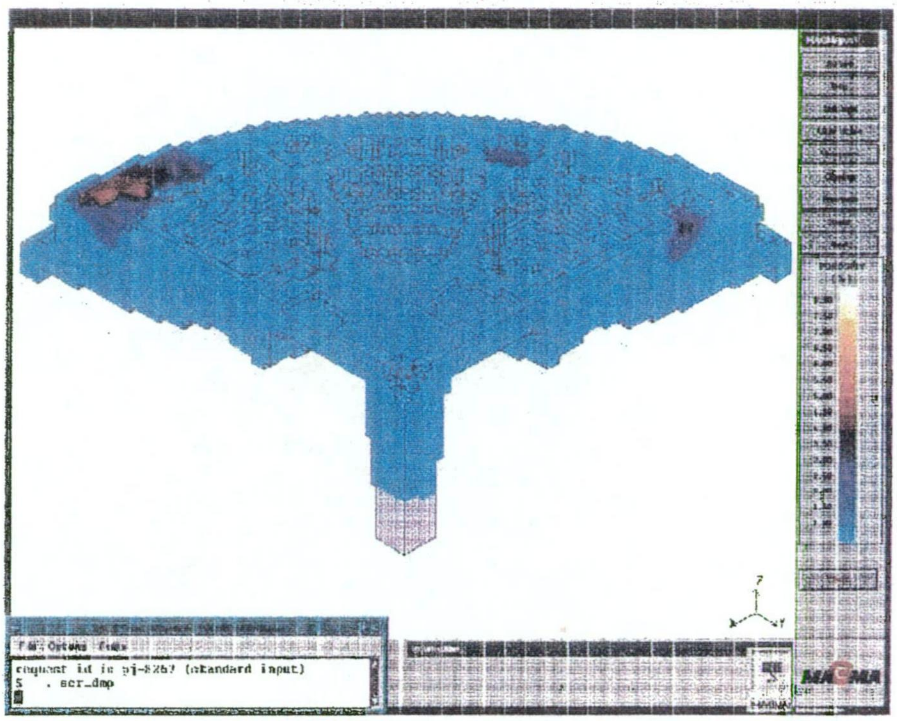


Figure 3.14: A Magma porosity output/prediction.

3. **% Solid:** This output as demonstrated as figure 3.15, it simply shows the cavity temperature but clearly distinguished between the solidus and liquidus of 601 metal ie metal below 542°C will be solid and metal above 542°C will be liquid. The output is important from a purely practical point of view. This is an important output purely from a practical point of view in that although an excellent thermal gradient may exist in the material at cycles end is liquid the result will be no practical product. The requirements of solid product and good thermal gradients can be at odds and compromises must be achieved.

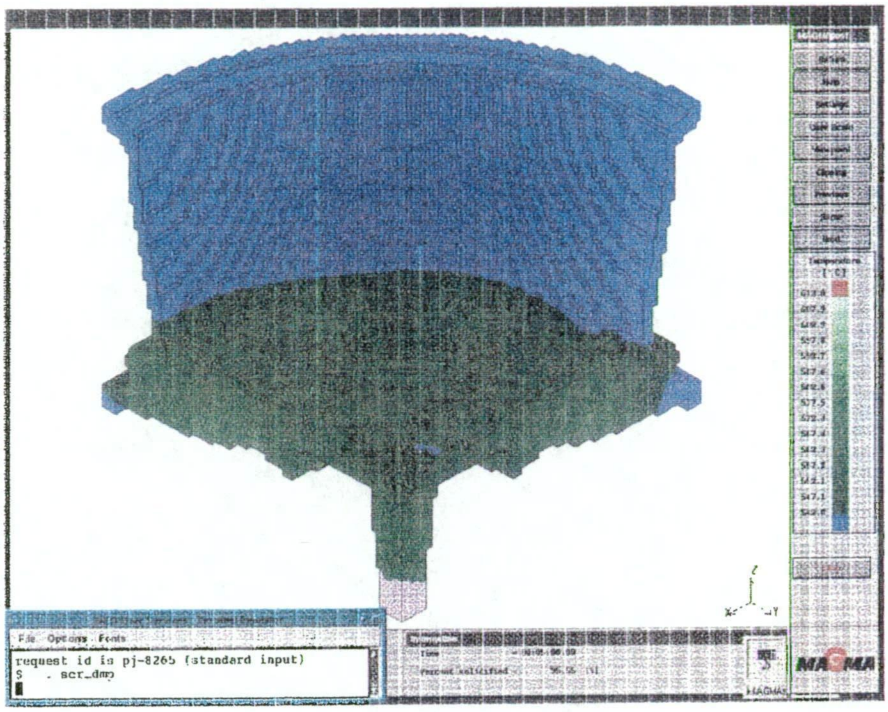


Figure 3.15: A Magma % solid output.

These criteria are used to determine the suitability and effect of various casting trials within the Magma environment.

3.5 Concluding remarks.

It has been shown in this chapter that the finite element analysis forms a very good basis for understanding the material behavior. In order to have a preliminary understanding of the qualitative trends of performance with respect to the major process variables, finite element modeling is considered as an adequate tool. This section highlighted that the reliability of quantitative trends, however, depended on the accuracy of magnitude of the loads applied at nodes. The finite element analysis is found to be applicable to the stress and strain analysis while the solidification rate is better analyzed using the finite difference methods. A commercially available software package, Magma is used to analyze both the cases. A brief description of the rationale and logic behind the software use is also presented. It has been found that the thin sections have a very high stress concentration, as expected, compared to the thin sections for the aluminum wheel under loading. Before identifying the minimum thickness a section can be cast, the procedure is verified using mechanical testing. A series of ultimate tensile strength, yield strength and elongation for the thin and thick sections using compressive testing machine have shown that the finite element analysis has reliable and comparable quantitative results. The other methods of finite element testing such as analysis of stresses using rotary bending have complemented the mechanical tests carried out.

The Magma is further analyzed using a Plackett-Burman screening design of experiment (DOE). It has been found that the DOE is a scientific method of minimizing the amount of experiments required while maximizing the effect of variable examination of the experiment. This section also highlighted the need to carry out DOE and understanding the directional solidification, porosity and % solid in a wheel casting. Again using Magma finite difference package, these aspects have been well analyzed. Understanding of directional solidification has shown that the temperature distributions in the casting process are uniform. This also increases the credibility of the uniformity of the metal used. From porosity point of view it is quite normal for good thermal gradient wheels to exhibit a low porosity prediction which the Magma output has complemented. In studying the % solid, the cavity temperature clearly distinguished between the solidus and liquidus of 601 metal ie metal below 542°C will be solid and metal above 542°C will be liquid. This is a further substantiation of the normal behavior of 601 aluminum alloy.

While it is encouraging to see that the qualitative and quantitative trends are comparable to both the mechanical testing, finite element analysis and DOE using Plackett-Burman procedure, there is a further need to verify these trends using experiments. In other words, after the finite element modeling there is a need to explore the practical dimensional limitations placed on any particular product, within the low pressure die casting environment. Before this is carried out on the available flexible manufacturing cell at SAPL, a brief review of the flexible cell will be discussed. As mentioned in earlier chapters, the casting part of the wheel manufacturing cycle is one of the highly sophisticated low-pressure die casting FMS cells in the country. The following chapter discusses the highly automated flexible casting cell at SAPL.

CHAPTER 4

FLEXIBLE MANUFACTURING CASTING CELL

The combined problems of constantly changing customer requirements, and a need to improve competitiveness for potential export markets, have caused many manufacturers (particularly automotive, aerospace and white-goods) to re-assess their current design and production methods. Short model lifespan and the need to make continual design changes within this lifespan, culminate in frequent compensation or re-tooling for traditional, dedicated (on-line) production equipment.

All these manufacturing techniques create a need for a flexible approach to production equipment, which can respond to smaller batches of changing components than have generally been encountered in the past. There are four basic approaches to production processes whether it is casting or machining- these being on-line (dedicated) transfer machine, the Flexible Transfer Line (FTL), the Flexible Manufaturing System (FMS) and the Flexible Stand-Alone Cell (FMC). While it is interesting to note that one of the types of automated cell is the flexible manufacturing system (FMS) an FMS integrates many of the concepts and technologies which include:

- Flexible automation
- Group technology
- Automated material handling between machines
- Computer control of machines

The first FMS installations in the US were made around 1967. These initial systems performed machining operations on families of parts using NC machine tools. By 1981, the FMS population had grown to about 25 in the US, 40 in Japan and 50 in Europe [6]. By the beginning of 1985, the number of flexible manufacturing system installations had reached an estimated 300 worldwide. These flexible manufacturing systems include casting cells, machining and welding cells. Before the detailed explanation of the casting flexible manufacturing cell incorporated at Southern Aluminium is discussed a brief overview of the associated principles and the constitution is discussed. The following section briefly explains the flexible manufacturing systems: their components, their operation, their applications and their significance. The specific operation of the FMS at southern aluminium will be covered from the point of view of the discussion below.

A *flexible manufacturing system,* by definition, consists of a group of processing stations (predominantly automated machine tools), interconnected by means of an automated material handling and storage system, and controlled by an integrated computer system. What gives the FMS its name is that it is capable of processing a variety of different types of parts simultaneously under NC program control at the various workstations. The initials FMS are sometimes used to denote the term *flexible machining system*. The automated casting process is presently the largest application area for FMS technology. However, it seems appropriate to interpret FMS in its broader meaning, allowing for a wide range of possible applications beyond casting and machining.

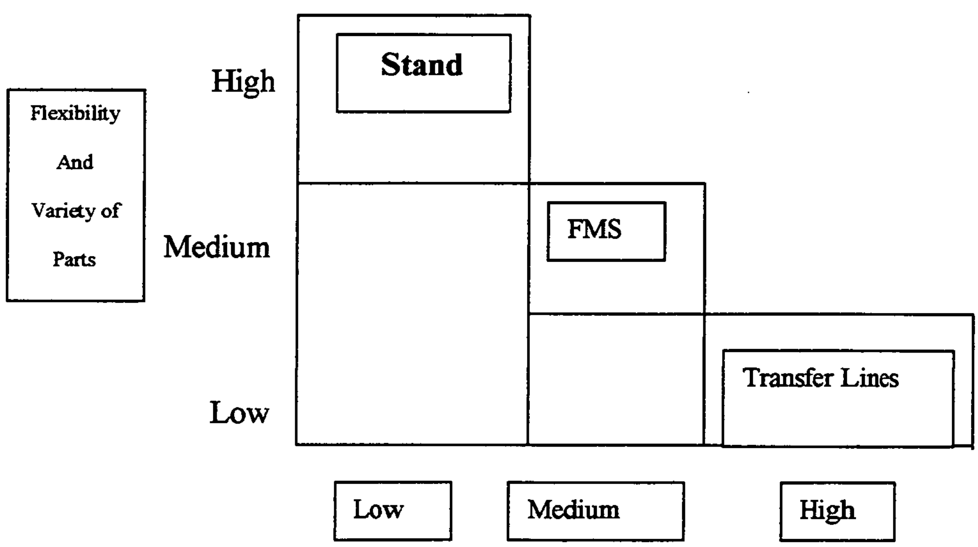
As indicated in the definition above, there are three basic components of a flexible manufacturing system: processing stations, material handling and storage and computer control. The processing stations or the workstations are typically computer numerical control machine tools that perform the entire cycle of the casting process by the computer which controls pressure and temperature at all stages. However, flexible manufacturing systems are being designed with other types of processing equipment, including inspection stations, assembly workheads, and sheet metal presses. Some of the issues involved in selecting the equipment used in these processing stations will also be discussed in these presents. The other component of FMS is the material handling and storage system. Various types of automated material handling equipment are used to transport the workparts and subassemblies between the processing stations, sometimes incorporating storage into the function. Finally the heart of all the FMS is the computer control system which is used to coordinate the activities of the processing stations and the material handling system in the FMS. In a semi automated FMS, however, one more additional component exists in the form of human labour. Human beings are needed to manage the operations of the flexible manufacturing system. Functions typically performed by people include loading raw workparts onto the system, unloading finished parts (or assemblies) from the system, changing and setting tools, equipment maintenance and repair, NC part programming and operating the computer system.

There are various ways to classify flexible manufacturing systems. One classification that is sometimes made in FMS terminology is the difference between a flexible manufacturing system and a manufacturing cell. There is no clear dividing line. Generally, the term cell can be used to refer to a machine grouping that consists of either manually operated or automated machines, or combinations of the two. The cell may or may not include automated material handling, and it may or may not be computer controlled. The term "flexible manufacturing system" generally means a fully automated system consisting of automated workstations, automated materials handling, and computer control.

The term *manufacturing cell* is used largely in connection with group technology, but both cells and FMSs rely on a group technology approach in their design. A distinction that is sometimes made between a flexible manufacturing cell and a flexible manufacturing system is in the number of machines in the grouping. A grouping of four or more machines is a system, and three or fewer machines constitute a cell. For example, a grouping of several machines served by a robot and capable of processing a family of parts is commonly called a *flexible manufacturing cell*. Flexible manufacturing systems can be described as being either a dedicated FMS or a random-order FMS. A dedicated FMS is used to produce a much more limited variety of part configurations. The geometrical differences are minor and the product design is considered stable. Therefore, the machine sequence is identical or nearly identical for all parts processed on the system. This means that a flow line configuration is generally most appropriate for a casting process so that the system can be designed with a certain amount of process specialization to make the operations more efficient. Instead of using general-purpose machines, the machines can be designed for the specific processes required to make the limited part family. The aluminium wheel manufacturing FMS at Southern Aluminium, for example, is a very specialised flexible manufacturing system.

The random-order FMS is the more appropriate type under the following conditions: where the part family is large; there are substantial variatons in the part configurations, there will be new part designs produced on the system and engineering changes in parts currently made on the system, and the production schedule is subject to change from day to day. This is a typical situation for machining centres. The machining flexible manufacturing cell at Southern Aluminium is a typical example for the above mentioned conditions. To accommodate these variations, the random-order FMS must be more flexible than the dedicated FMS. It is equipped with general-purpose machines to deal with the variations in product and is capable of processing parts in various sequences (random order). A more sophisticated computer control system is required for this FMS type.

Flexible manufacturing systems are considered to fill a gap between high-production transfer lines and low-production NC machines. The relative position of the FMS as a means of production is shown in Figure 4.1.



PRODUCTION VOLUME

Figure. 4.1. Application Characteristics of Flexible Manufacturing Systems

For high volumes and output rates, transfer lines represent the most efficient method. The limitation of the transfer line is that variations in product configuration cannot be readily tolerated. A substantial redesign of the product may render this mode of production obsolete. On the other hand, stand-alone NC and CNC machines can accommodate changes in part configuration, but the production rates are substantially lower and the parts are usually made in batches. In terms of manufacturing efficiency and productivity, a gap exists between the high-production transfer line and the highly flexible NC machines. The solution to this midvolume production problem is the flexible manufacturing system. In the midvolume range, the advantages of the FMS over stand-alone NC is that the production of several products can be intermixed, and production rates are higher. Instead of batching the products one at a time on an NC machine to meet requirements, the various products can be made simultaneously on the system. The setup time for changeover is minimized with an FMS, so the economic batch size reduces to one at the same time that the average production rate increases. Intermixing of products on the system permits the output rate of each product to be set at its corresponding demand rate. This reduces the work-in-process and final product inventories that are so typical of batch production methods.

The advantage of the flexible manufacturing system over a transfer line is flexibility. The FMS can be used to run a variety of product configurations, whereas the transfer line can produce only one or a limited number of product types. The processing or assembly equipment used in a flexible manufacturing system depends on the type of work that is accomplished on the system. In a system designed for casting operations, the principal types of processing station are CNC tools. However, the FMS concept is being applied to various other processes as well. Following is a list of the types of machines used in FMS workstations.

Casting centers The CNC casting center in its use as a highly automated stand-alone machine, it can be used as a component of a flexible manufacturing system. It possesses features that make it very compatible with the FMS approach to production, including automatic tool changing and tool storage, use of palletized workparts, CNC control, and capacity for DNC control.

Work changers For specialized casting applications involved in continuous production, automated work changing facility should be provided. A work changer is a special machine tool accessory with the capability to change high temperature castings. These are tool modules that can be stored on a rack or drum located on or near the specialised machine for automatic workmaterial handling. Higher production rates can be achieved than when the operations are performed one at a time. Because of the high cost of the tooling involved, work changers are useful only where production volume is sufficient to justify the savings in production time.

Assembly workstations Some flexible manufacturing systems include assembly within the scope of their operations. Indeed, flexible automated assembly systems are being developed to replace manual labour in the assembly of products typically made in batches [28]. Industrial robots are usually considered to be most appropriate as the automated workstations in these flexible assembly systems. They can be programmed to perform tasks with variations in sequence and motion pattern to accommodate the different product styles made on the system.

Inspection stations Inspection can be incorporated into a flexible manufacturing system, either by including an inspection operation at a given workstation, or by designating a specific station for inspection. Coordinate measuring machines, special inspection probes that can be used in a machine tool spindle, and machine vision represent three possible methods of performing inspection on an FMS. Inspection has been found to be particularly important in flexible assembly systems to ensure that components have been properly added at the workstations as specified. We examine the topic of automated inspection in more detail, where the notion of a flexible automated inspection system is introduced.

Forging stations Flexible systems are being developed to automate the forging process. Forging is traditionally a very labour intensive manufacturing activity. The workstations in the system consist principally of the heating furnace, the forging press, and a trimming station.

A brief review of several workstations used in flexible manufacturing systems is discussed below. Material handling and storage systems are major components of an FMS is its material handling and storage system. The material handling and storage system in a flexible manufacturing system should perform the following five functions:

1. Random, independent movement of workparts between workstations. This means that parts must be capable of moving from any one machine in the system to any other machine. This allows the system to achieve various processing sequences on the different machines in the cell, and to make substitutions when certain machines are busy.

2. Handle a variety of work part configurations. For example, different automobile manufacturers have their aluminium wheel specifications and the work handling should be flexible to cater for various designs. The fixture is located on the top face of the pallet and is designed to accommodate different part configurations by means of common components, quick-change features and other devices that permit a rapid builtup of the fixture for a given part. The base of the pallet is designed for the material handling system. For subsequent operations during the casting process such

as quenching, industrial robots are often used to load and unload the hot castings [2] and to transfer parts between workstations.

3. Temporary storage The number of parts in the FMS typically exceeds the number of parts actually being processed. In this way, each machine can have a queue of parts waiting to be processed. This helps to increase machine utilization.

4. Convenient access for loading and unloading workparts. The handling system must provide a means to load and unload parts from the FMS. This is often accomplished by having one or more load/unload stations in the system. Manual operators are used to build up the pallet fixtures, load the parts and unload the finished parts when processing has been completed.

5. Compatible with computer control. The handling system must be capable of being controlled directly by the computer to direct it to the various workstations, load and unload stations, and so on.

Once the workstations, work handling devices and computer control are sorted out the lay out of FMS becomes a very important issues. The types of layout configurations commonly found in today's flexible manufacturing systems can be divided into the following five categories [[28]]:

1. In-line
2. Loop
3. Ladder
4. Open-field
5. Robot-centered cell

The in-line configuration is illustrated in Figure 4.2. It is most appropriate for systems in which the parts progress from one workstation to the next in a well-defined sequence with no back flow. The operation of this type of system is very similar to a transfer line. Work always flows in one direction, as shown in Figure 4.2(a). Depending on the flexibility and storage features of the handling system it is possible to accommodate back flow of work on the system. One possible arrangement for doing this is shown in Figure 4.2(b) in which a secondary work handling system is provided at each workstation.

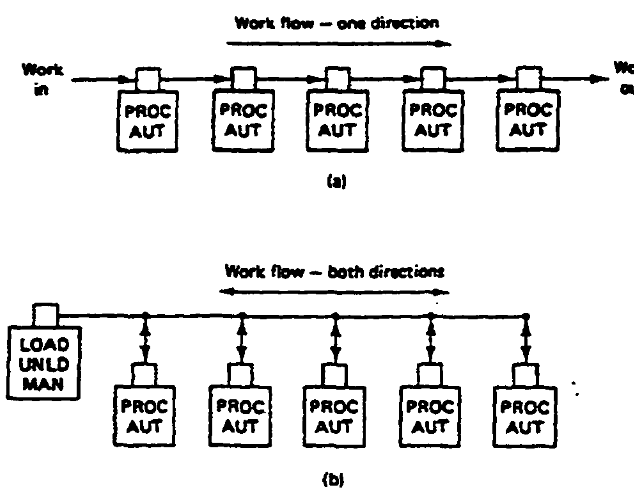


Figure. 4. 2 In-Line FMS Layout (a) one direction, (b) both directions

The basic loop configuration is shown in Fig.4.3. Parts usually flow in one direction around the loop with the capability to stop at any station. The load/unload station(s) are typically located at one end of the loop. A secondary handling system is shown at each workstation to permit parts to move without obstruction around the loop. The Ingersoll-Rand FMS described in our first application example and illustrated in Fig.4.3uses a loop configuration.

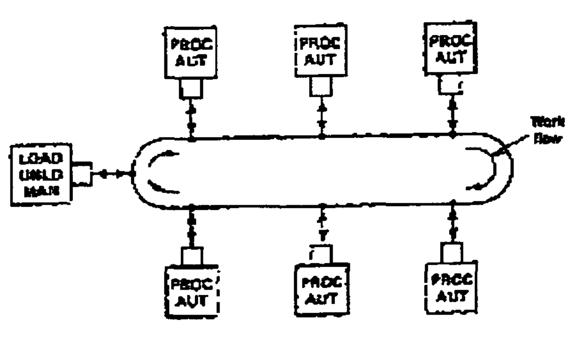


Figure: 4.3. Basic Loop Configuration

The ladder configurationis an adaptation of the loop, as shown in Fig.4.4. It contains rungs on which workstations are located. The rungs increase the possible ways of getting from one machine to the next. This reduces the average travel distance, thereby reducing the transfer time between workstations.

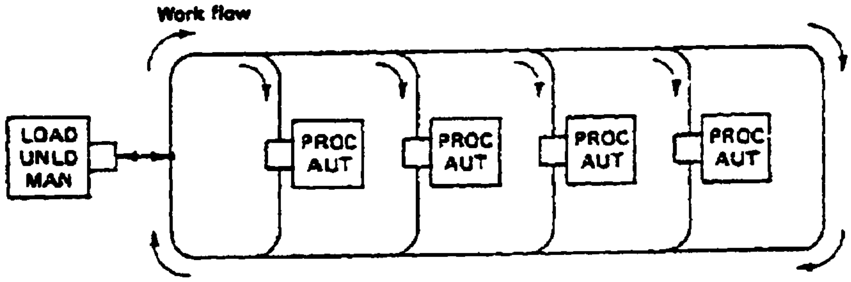


Figure. 4.4. Ladder FMS Layout

The open-field layout is also an adaptation of the loop configuration. It consists of loops, ladders and sidings organized to achieve the desired processing requirements. This layout type is generally appropriate for the processing of a large family of parts. The number of different machine types may be limited, and parts are routed to different workstations depending on which one becomes available first.

After the layout there is a need to discuss how the material handling is carried out in the factory. The types of material handling equipment that have been used to transfer parts between stations in an FMS include: roller conveyors, cart-on-track conveyors and other types of conveyor systems; in-floor towline carts; automated guided vehicle systems (AGV's); and industrial robots. From southern aluminium company point of view, the material handling is handled by both AGV's and roller conveyors after the casting at FMS to carry the wheels to subsequent manufacturing processes.

These materials handling systems constitute what is sometimes called the primary material handling system in the FMS. The primary handling system establishes the basic form of the layout configurations described in the preceding subsection. The types of material handling equipment typically utilized for the five FMS layouts are summarized in Table 4.1. In addition to the primary handling system, many FMS installations make use of a secondary handling system. The secondary handling system is located at each workstation and is used to transfer work from the parimary system to the machine tool or other processing station. Its function is to position and locate the parts with sufficient accuracy and repeatability at the workstation for processing. Buffer storage of parts may also be provided at each workstation by the secondary system.

Table 4.1: Material Handling Systems Typically Used for the Five FMS Layouts

Layout Configuration	Typical material handling system
1. In-line	Conveyor system, shuttle system
2. Loop	Conveyor system
3. Ladder	Conveyor system, AGVS
4. Open field	AGVS, in-floor towline carts
5. Robot-centered cell	Industrial robot(s)

In some FMS installations, the secondary handling system is not included. All of the positioning and registration requirements at the individual stations are satisfied by the primary work handling system. From southern aluminium point of view the primary material handling suffices the need and secondary handling system was not installed.

The last of the major constituents in FMS is the operation of a flexible manufacturing system using a computer control. The functions of the computer, the data files needed to carry out these functions, and typical kinds of reports generated by the computer key tools for proper function of FMS.

The functions performed by the FMS computer controlled system can be grouped into the following eight categories [27] .

1. *Control of each workstation.* In a fully automated FMS, the individual processing or assembly stations generally operate under some form of computer control. For a casting system, CNC is used to control the individual casting cells.

2. *Distribution of control instructions to workstations.* Some form of central intelligence is also required to coordinate the processing at the individual stations. In a casting FMS, part programs must be downloaded to the machines, and DNC is used for this purpose. The DNC system stores the programs, allowing entering and editing of programs as needed, and performs the other DNC functions. This program executes the entire casting cycle.

3. *Traffic control.* The term traffic control refers to the regulation of the primary workpiece transport system which moves parts between workstations. This control is effected by dividing the transport systems into zones. For a typical casting FMS there are few castings waiting, some in process and a few just completed. All the three activities are taking place at any given time. This traffic operates the switches between the three phases of operation so that the parts move smoothly between stations. Traffic control is very similar to AGV's zone control.

4. *Production control.* This function includes decision on the selection of die for a casting process. For example, from a range of wheels to be cast, number of castings to be produced at the end of a week for different types need to be decided. The production plan incorporated by the computer decides which particular wheel casting should be produced to meet the production schedule. These decisions are based on data entering into the computer, such as desired production rate per day for various parts, numbers of raw workparts available, and number of applicable pallets. The computer performs its production control function by routing an applicable pallet to an load/unload area and providing instructions to the operator.

5. *Shuttle control.* This is concerned with the regulation of the secondary part handling systems at each machine tool. Each shuttle system must be coordinated with the primary handling system, and it must also be synchronized with the operations of the machine tool it serves.

6. *Tool control*. Monitoring and control of cutting tool status is an important feature of a FMS computer system. There are two aspects of tool control: accounting for the location of each die in the FMS and die condition monitoring.

7. *Work handling system monitoring*. The computer must monitor the status of each cart and/or pallet in the primary and secondary handling systems as well as the status of each of the various workpart types in the system.

8. *System performance monitoring and reporting*. The FMS computer can be programmed to generate various reports desired by management on system performance.

The casting FMS at Southern Aluminium is laid out in such a manner so to ensure minimal handling and maximum output. It has the ability to accept all types of product, it includes different wheel types and can also include different products. In is not uncommon within the operation for 4 different cavities with 4 different products. The experiments to decide on the dimensional limitations for minimum casting thickness are carried out in this FMS. A brief discription of the set up is given below.

The basic aspects of the process that need to be explained in this set up are the following:
The operational layout.
The low pressure fill.
The die operation, specifically with respect to the directional solidification.

Each of these is described below:

4.1 The operational layout

This is represented in fig.4.5, essentially showing the casting workstation. The operation consists of a number of significant operations. A normal operation sequence follows in fig 4.6, but first we need to understand the layout of the actual FMS used within the Southern Aluminium operation, this is represented both diagramatically and with some photographs.

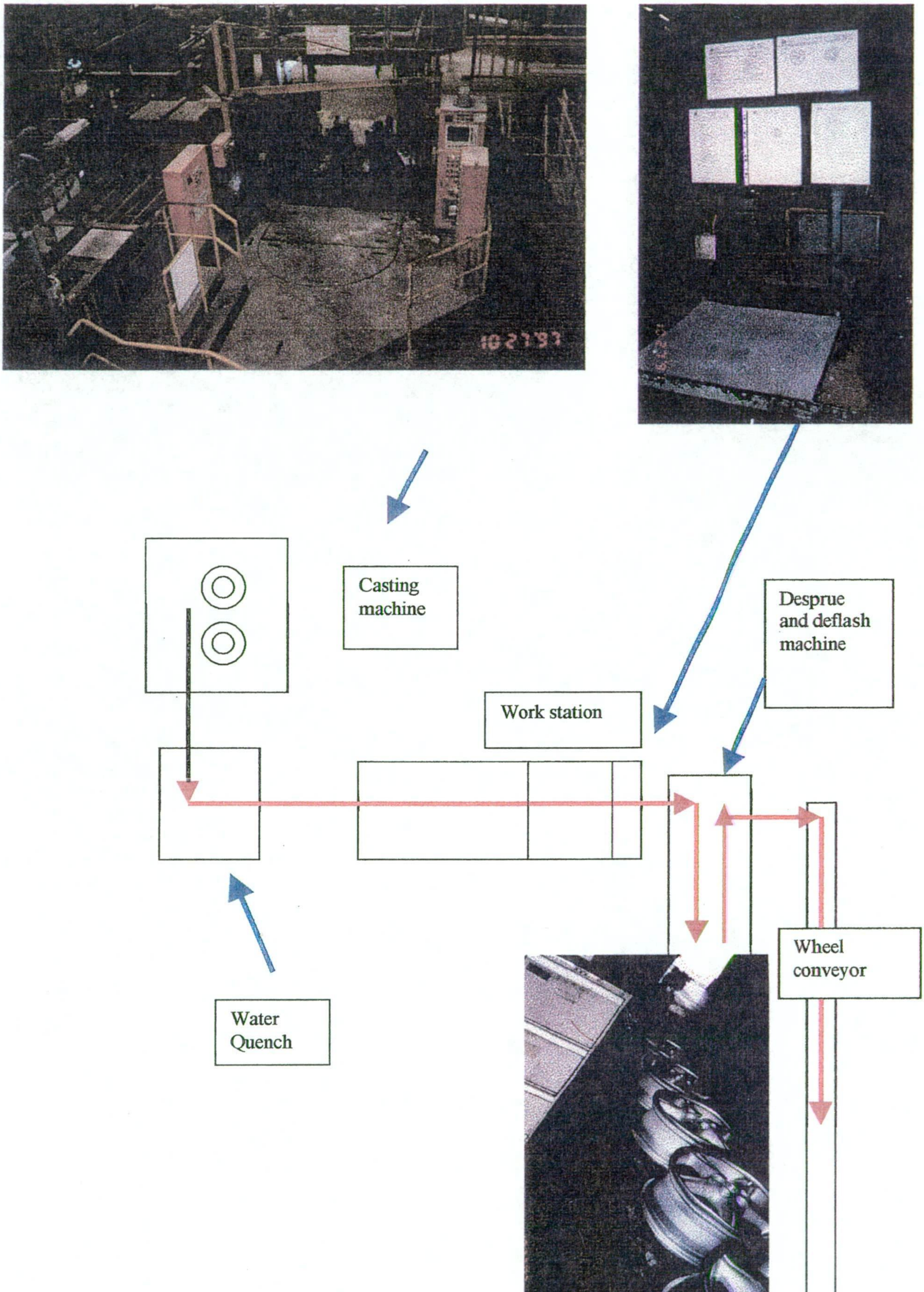


Fig 4.5 – Operational layout showing material movement in the casting area.

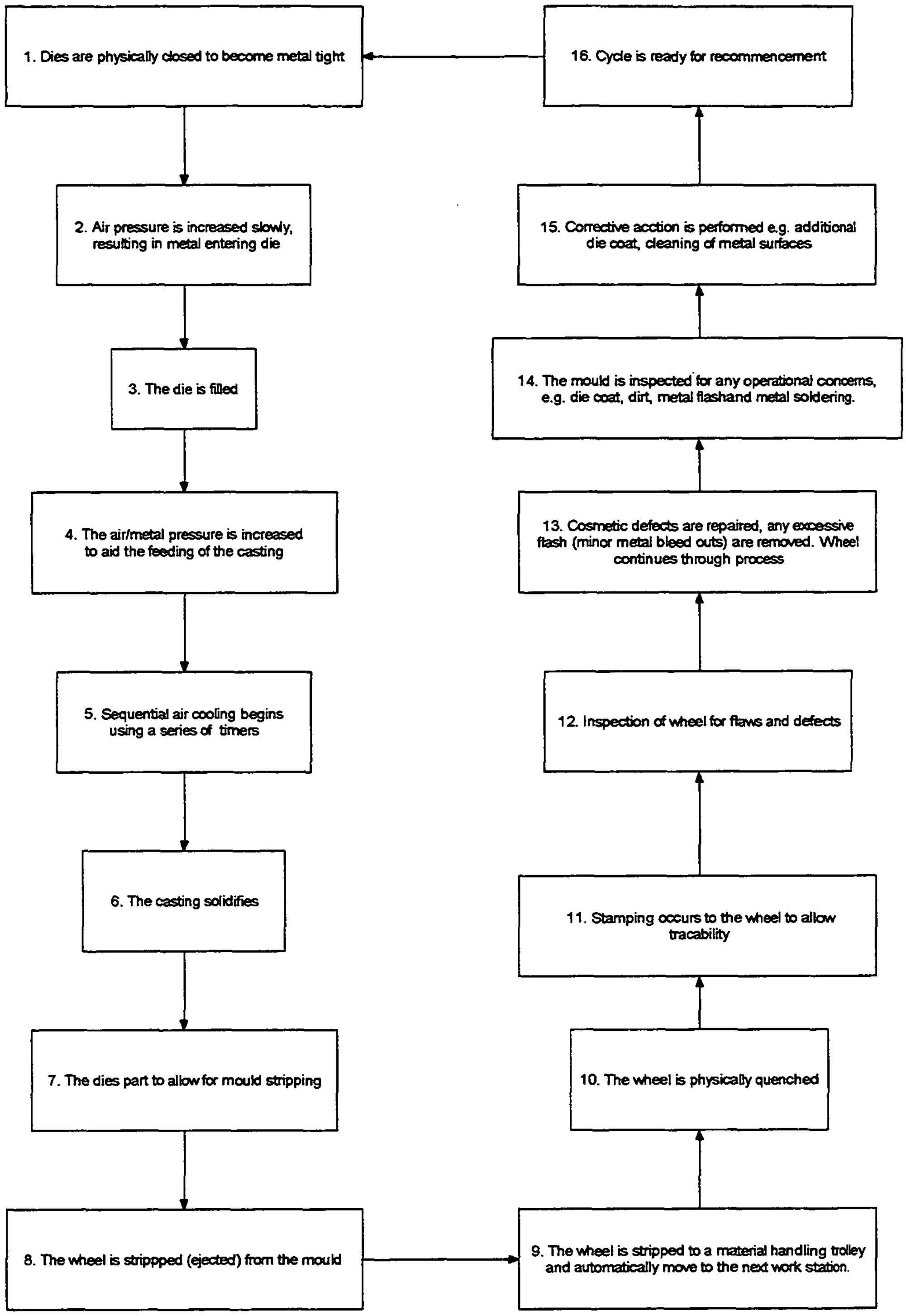


Figure 4.6 – Representation a complete operational cycle

The above cycle is repeated for each shot and Southern Aluminium the combination of shots is referred to as a production run.

4.2 The low pressure fill

The fundamental aspect of low-pressure casting is the low pressure used to fill the die. As described in chapter 1, low pressure casting refers to the pressure applied to a container of metal to enable metal to move up a riser tube which then consequently fills a die. It has two main advantageous, one the die is filled in a slow controlled manner minimizing turbulence. The pressure fill that is used on the metal can be described with the following equation.

$$p = \rho gh + FF$$

Or

$$p(pressure) = \rho(density)g(gravity)h(height) + FF(frictional\ forces)$$

In the low pressure environment density will remain constant (liquid metal) and the force of gravity will also remain constant. The frictional forces resulting from metal movement are minimal and can be assumed to be zero, specifically with the metal velocities used. The following equation can now be simplified.

$$p \propto h$$

Or

$$p = Ch$$

Where p is pressure C is a constant and h is height.

This equation 4.4 can now be used to establish the appropriate pressures for casting any particular product with respect to the machines/heights used from the metal face. A representation of a typical low-pressure casting curve is given with figure 4.6.

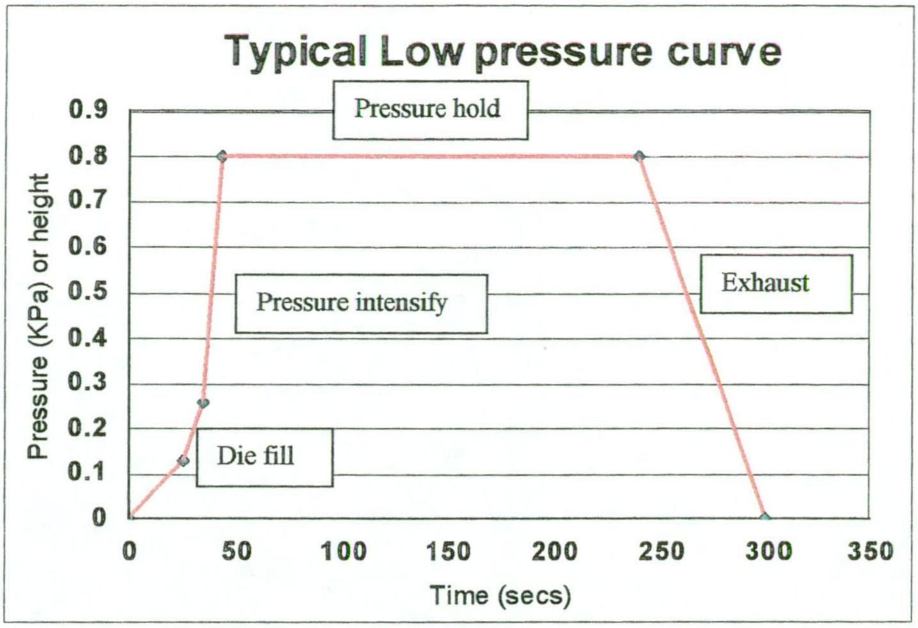


Figure 4.6 – Typical low-pressure casting curve showing critical elements (see explanation of terms).

1.1 Explanation of terms (fig 4.6).

1. Die fill – This refers to the period during low-pressure fill in which the die or cavity is actually filled. The major advantage of low-pressure casting is that die is filled in a slow controlled manner with as little turbulence as possible.

2. Pressure Intensified – Once the cavity has been filled it is advantageous to increase the metal pressure into the die as fast as possible. This is referred to as pressure intensification. This process aids the feeding of the metal and hence minimizes the possibility of shrinkage.

3. Pressure hold – The time in which the pressure remains on the metal. During pressure hold the material will become completely solid.

4. Exhaust – The time taken for the metal pressure to be released from the die, this will enable die stripping to take place.

4.3 - The die operation.

The fundamental aspect of all casting processed is to allow for directional solidification to take place. in order to achieve this the die/cavity must be setup in a manner to allow this to take place. the result of this will be discussed in chapter 5, but in order to enable better understanding of the die layout the following figure is shown, see figure 4.7.

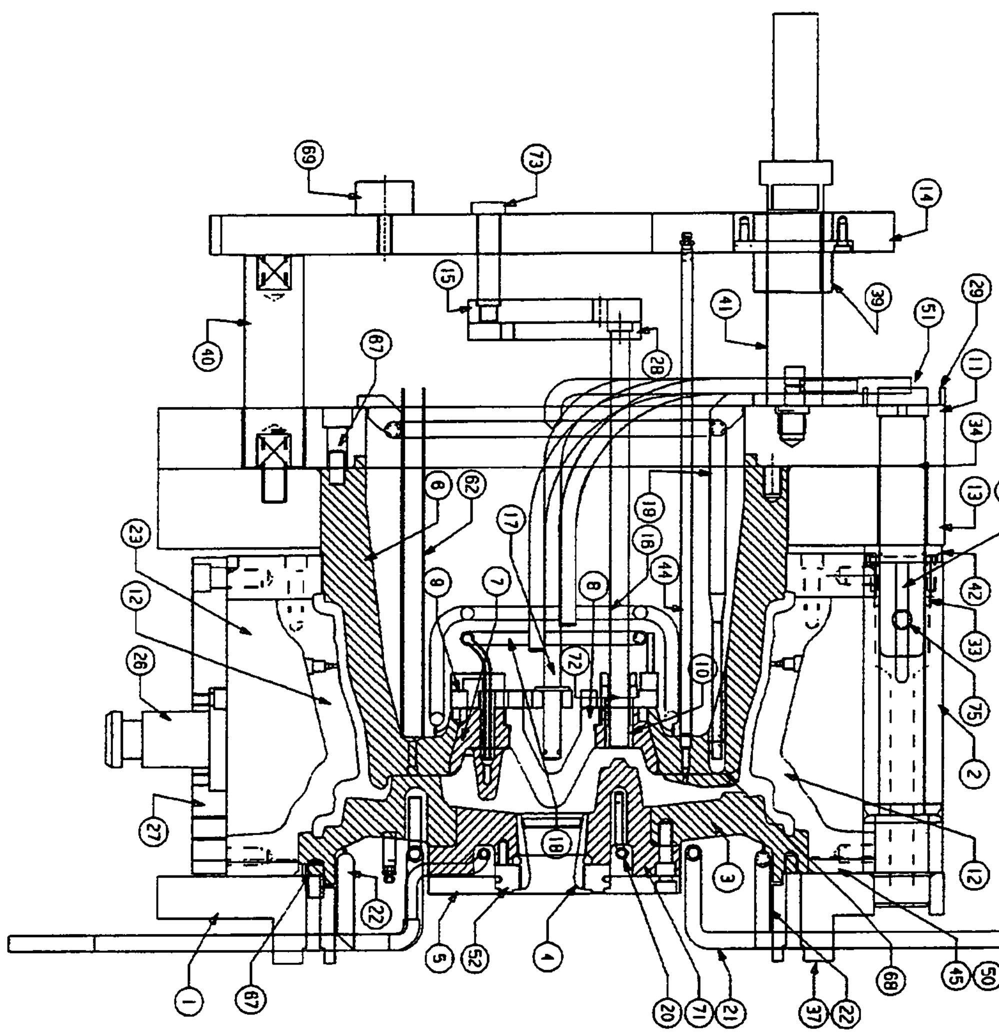


Figure 4.7: Operational layout of Die used at Southern Aluminium

The above diagram is a full operational explanation of the operational layout the above diagrams demonstrates the aspect of die operation and the cooling possibilities to enable complete good directional solidification behaviour. The cooling channels displayed are the major process control that can be enabled and optimised during a production run and can also be used with the Magma solidification package. These will be discussed below in normal sequence of cooling. All cooling used in above layout is air cooling, no other cooling is available. The cooling sequence used is explained below which is used to assist in directional solidification. The cooling sequence and its effect is investigated using the DOE experimental technique.

Table 4.2 : Air cooling sequence used to demonstrate directional solidification the numbers refer to figure figure 4.7.

Cooling channel turned on first

19. Spoke cooling channel, usually on early to cool spoke rim intersection.

21,22. Rim/Disk cooling. As with spoke on early to cool spoke rim intersect.

16. Hub cooling, next applied to promote directional solidification, toward feed or centre of the wheel.

17. Centre pin cooling, Used to cool and solidify the centre of the wheel prior to ejection.

20.Gate cooling, Final cooling applied to form and solidify sprue immediately prior to ejection.

Cooling Channel turned on last.

4.4 Concluding remarks

A description of the flexible manufacturing system, the casting process both from an operational and a technical perspective has now been described. This Flexible manufacture system in combination with the tools provided sets various operating parameters, which in the using of the above flexible manufacturing system allows us to determine from a theoretical and a practical point of view the dimensional limits limitations for low-pressure die-casting. The following chapter describes the nature of investigations and quantitative results achieved in casting minimum thickness sections for aluminium wheel castings.

CHAPTER 5

QUALITATIVE AND QUANTITATIVE VERIFICATION OF CASTING DIMENSIONS

In order to understand the dimensional limitations of the low-pressure casting process various separate elements need to be discussed in relationship to the requirements. The product produced must fulfil the requirements being easy to manufacture, pass all mechanical test requirements, and fulfil the customer requirements of weight function and style.

In order to demonstrate this the minimisation of various dimensional aspects of low pressure casting, the casting is separated into 2 main functions these include:

1. The ability for the product to be manufactured in the non feed area of the wheel, this includes 2 main functions, one being the ability for the product to form reliably and maintain its structural integrity.

2. The ability for the product to be manufactured in the feed area of the wheel, this includes the ability for the product to overcome the volume difference between liquid and solid, and if possible maintain or improve the structural integrity of the product.

5.1 <u>Ability to Manufacture and pass stress requirements</u>:

This refers to those areas of the wheel that are not subject to feed. Feed being defined as an area of the wheel that does not take part in the function of overcoming the function of the solid to liquid volume difference. This area is necessary to the wheel for the functions of strength and style. The ability to manufacture is defined as the production of a component with minimum reject rate. The low-pressure casting process employed at Southern Aluminium must produce this part of the wheel with maximum yield.

In order to understand the practical limitations on the product thickness the experiment shown below which demonstrates the relationship between product thickness and the product yield specifically to the area as defined as a non feed area. The example that follows clearly demonstrates the issue of minimal achievable thickness for a particular part of a wheel in the low-pressure casting process.

The following results are the average reject rate for various thickness of a particular component across a number of dies. The sample size to establish the following figures is greater than 500 wheels. . The experience was demonstrated in the FMS cell described in the previous chapter.

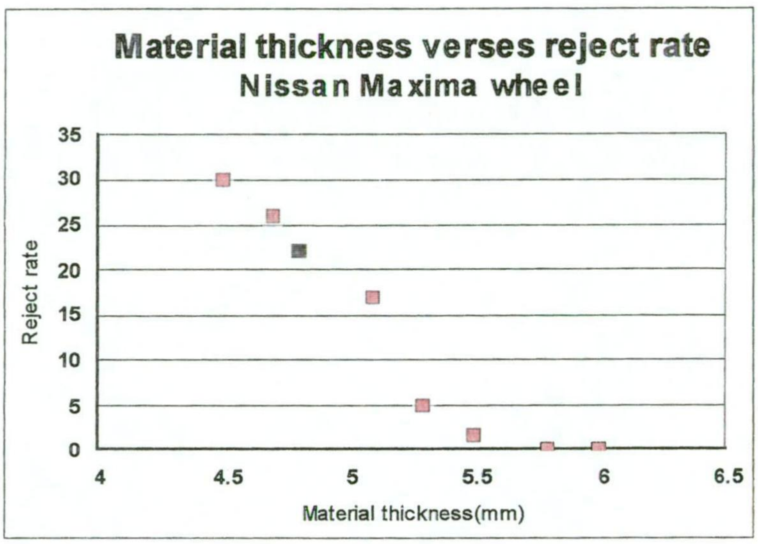


Fig 5.1 – Material thickness (non-feed) verses yield (reject rate) for a production wheel.

Figure 5.1 clearly demonstrates the critical nature of maintaining a critical dimension, with respect to the yield or reject rate. Specifically in the circumstances demonstrated a minimum dimension of 6 mm was required to achieve a 100% yield. It is worth noting that product can be produced with lower dimensions but at the expense of reject rate or in other words in a non-economic function. It should also be clearly understood that the figures represented above are in relationship to a particular product in a particular location, but it must be recognised that similar behaviour exist for a number of different product. Which includes product produced for Ford, Mazda, and Nissan as demonstrated above.

We have now demonstrated a clear dimensional minimum for the manufacture of a product. We now need to demonstrate the ability of the product to overcome the necessity to overcome the need to clearly survive the mechanical requirements of a structural component. To demonstrate the products ability to do this a new product was designed with the dimensional limit supplied above and the result are given below using the demonstrated FEA discussed in chapter 3.

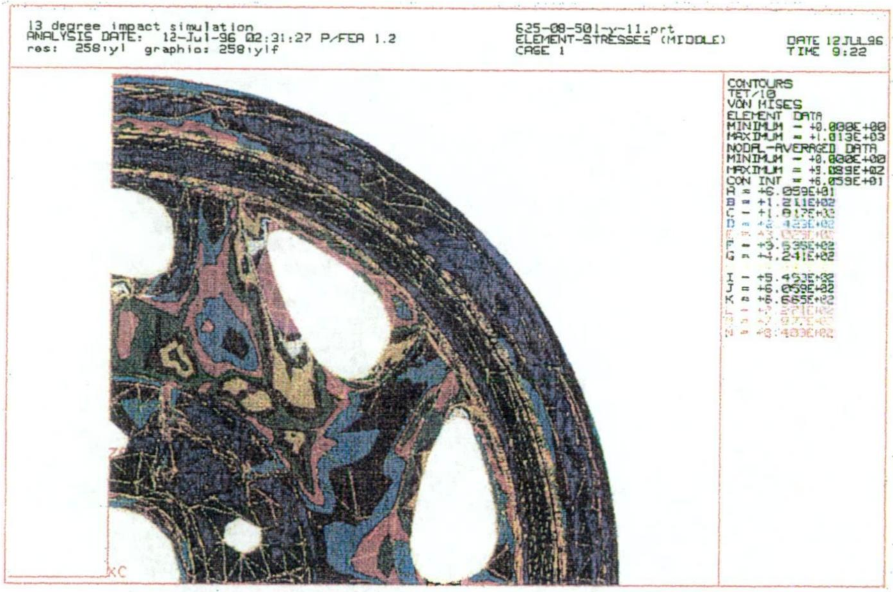


Figure 5.2 : Stress analysis of dimensional minimum wheel – Impact result

The stated output above produces a product showing a maximum stress level of 848 MPa, which is higher than the stated required high level of 800 MPa. Product produced with the casting process must survive high impact loadings and must survive them well. The need to pass this test well is demonstrated in figure 5.3, which gives an example of a methodology termed “staircase method” which is used to provide an output to determine the level of impact performance with a pass/fail test. What it does show however is the “normal” degree of variation associated with this particular test or more specifically the material. This was briefly discussed in chapter 3. The variation can be noted due to the difference in impact heights for what should be essentially the same product ie a wheel passed an impact height of 490mm and failed an impact height of 430 mm. This variation is an entire issue in itself, and will not be discussed here, but does demonstrate the need for product robustness and the conservative approach that is generally taken in wheel manufacturing.

Due to the high stress level, relative to the material performance, the above stress level is deemed unsatisfactory. Prior to alteration though the product is examined with the FDM solidification package to examine the products ability to pass the requirements of the casting process, the result of this is shown with figure 5.4.

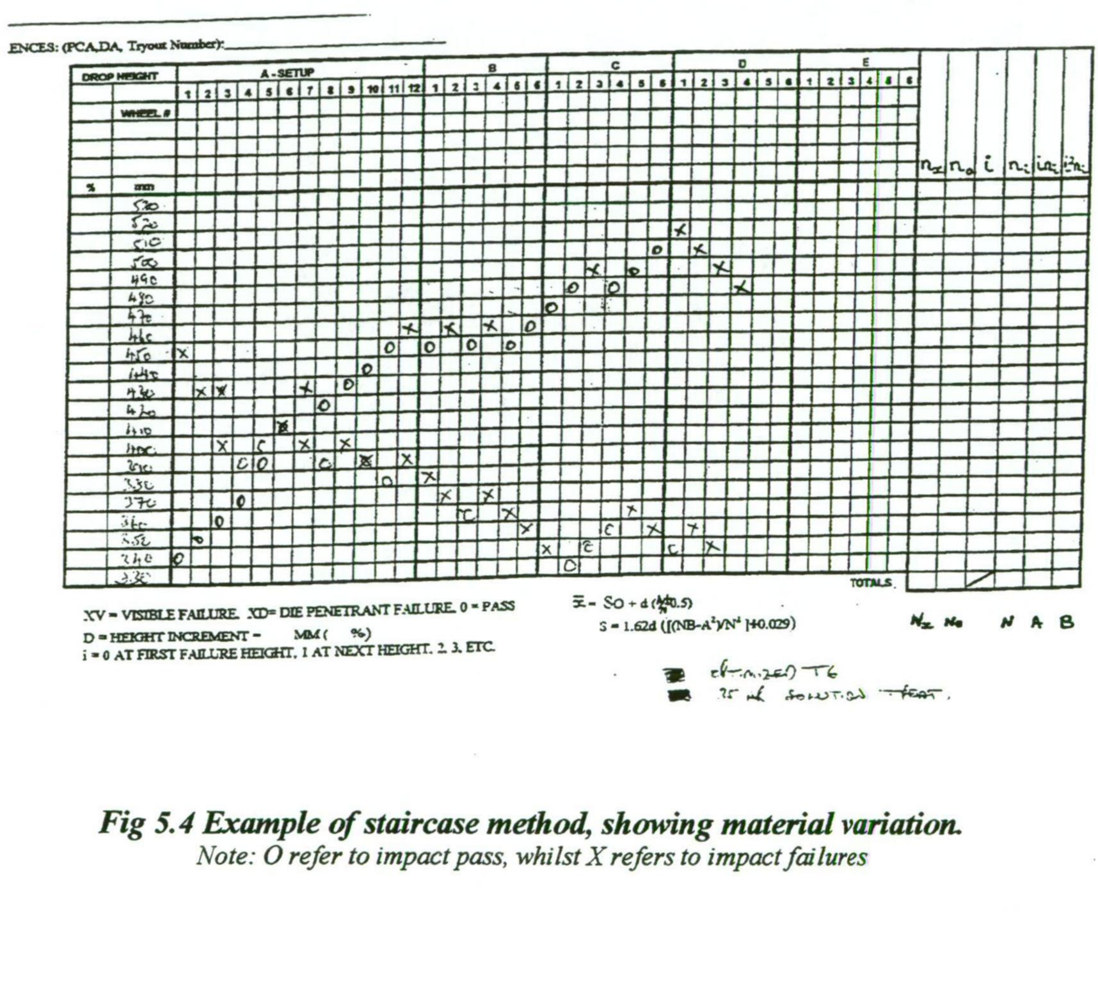


Fig 5.4 Example of staircase method, showing material variation.

Note: O refer to impact pass, whilst X refers to impact failures

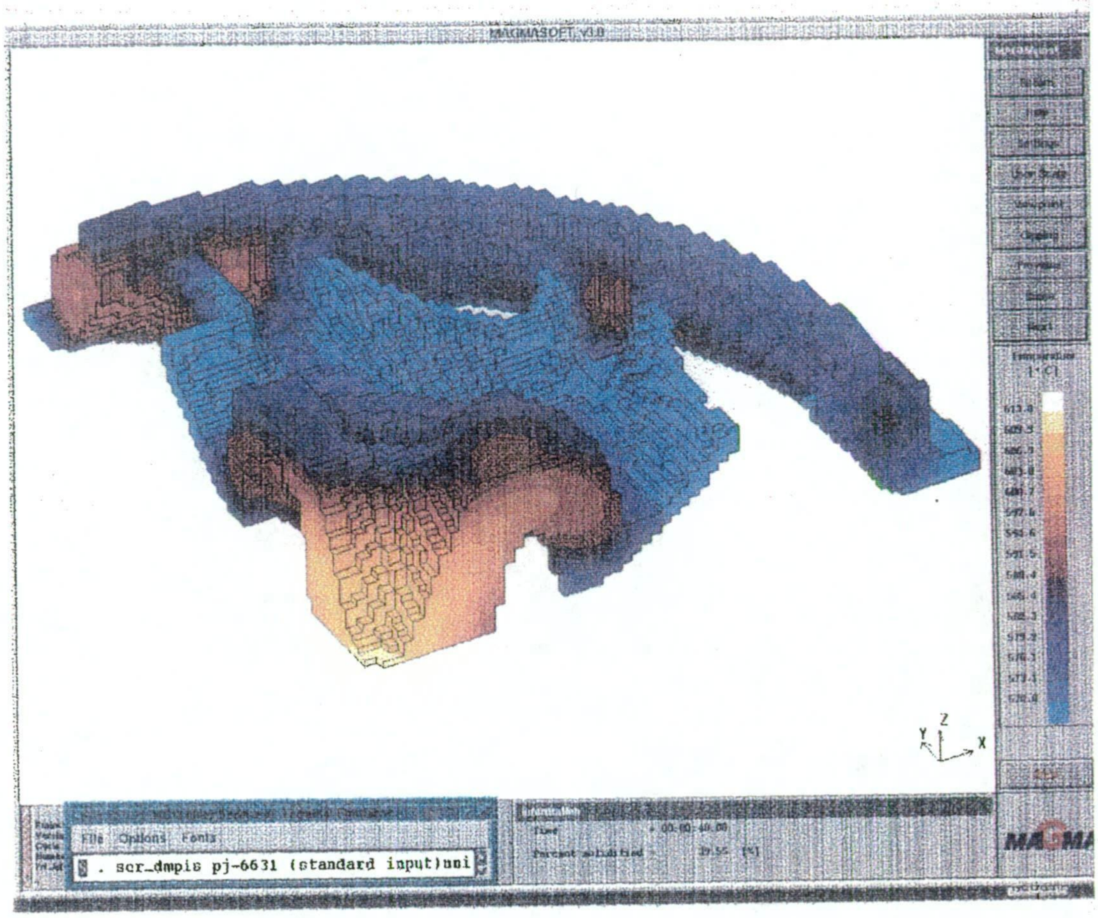


Figure 5.3 – Casting Simulation with dimensional minimum

The result of figure 5.3 clearly demonstrates the unsatisfactory casting nature of the product as it stands. The reasons for this are various and are based around the fact the material on the spoke will freeze prior to any substantial feed to the spoke rim intersect. Further investigation of the above product for casting performance using the DOE approach was not completed due to the failure of the component to pass the stress requirement.

In order to overcome the stress requirement the following trial was completed allowing for the continuation of dimensional minimus, but with the inclusion of a "stiffening rib" the stress output of this is shown in figure 5.4

Figure 5.4 – Above product component with "stiffening rib"

Figure 5.4 demonstrates the substantial shift in product performance with the inclusion of the stiffening rib, and although some local higher stress levels are evident it clearly demonstrates the redistribution of stress load on the product. In particular the stress associated with the window of the wheel has now be changed from a high of 848 MPa (considered unacceptable) to a current value of 509 MPa. This substantial improvement can be considered favorably, and provides a clear demonstration of the product direction that needs to be followed in order to make a good economic product. It should be noted that the addition of the "stiffening rib" is in compliment to the solidification requirement of extra material in the rib area to provide substantially better feed. Figure 5.5 demonstrates the substantial product improvement with a feed rib (similar but not identical) to the rib demonstrated within the FEA stress package. The appropriately sized feed rib should now be discussed in relation to empirical product performance.

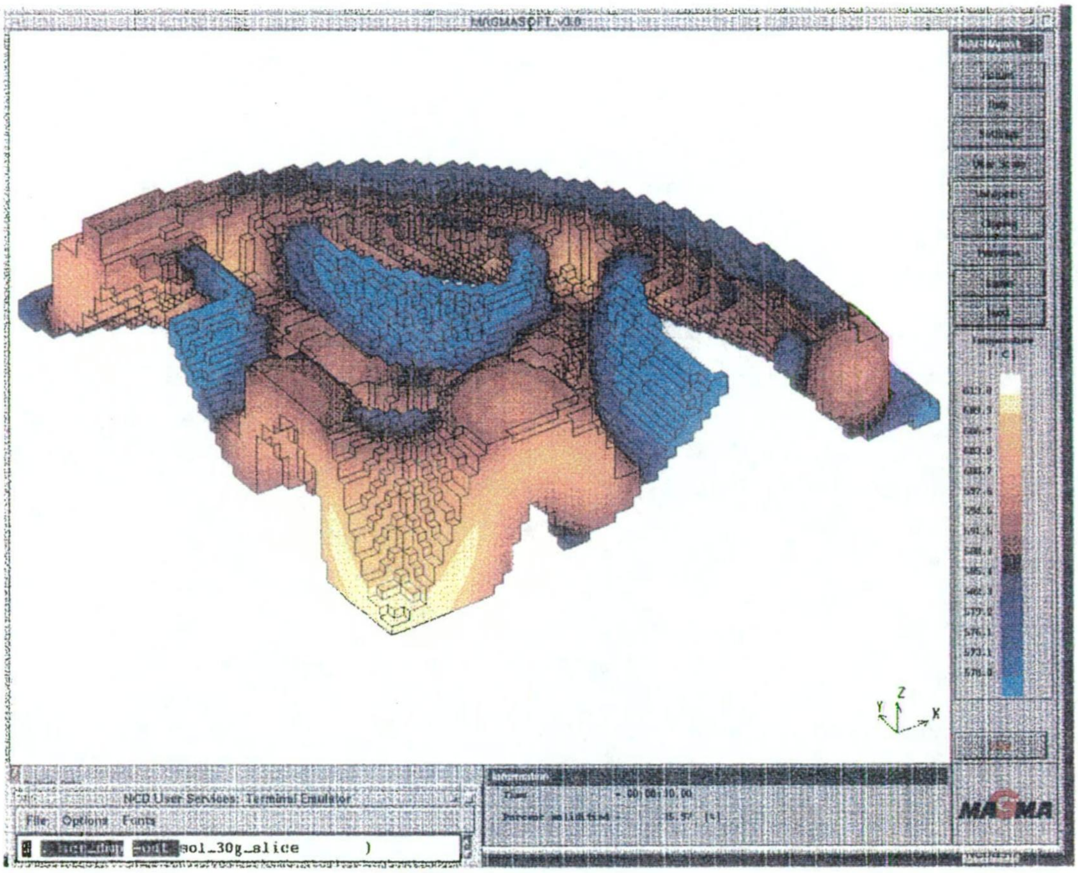


Figure 5.5 – Results of the use of a "feed" rib.

The result demonstrated using the above FDM Magma analysis has been verified by a significant trial of over 100 wheel castings at each of the above stated feed conditions. The trial was conducted using near identical casting conditions. In the trial the measure of feeding success was specified as visible porosity due to the fact that visible porosity is present when the feeding regime is inadequate. Figure 5.6 clearly demonstrates the improvement in casting present with the extra feed.

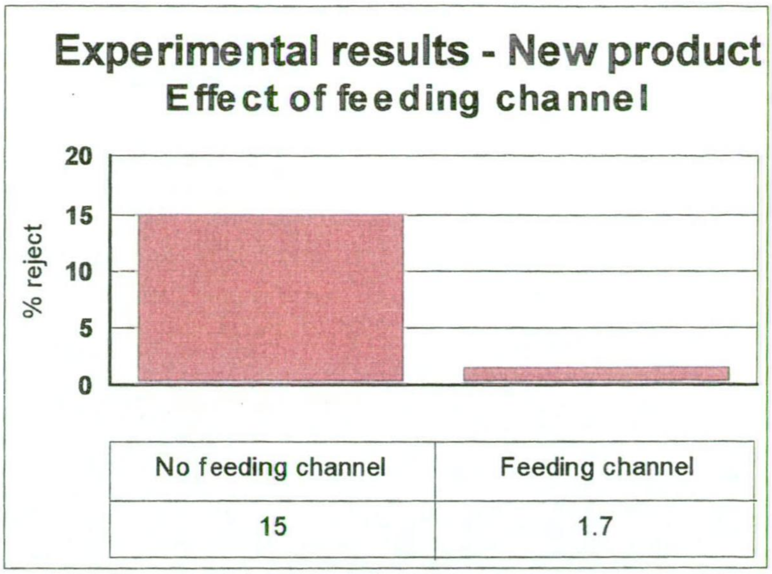
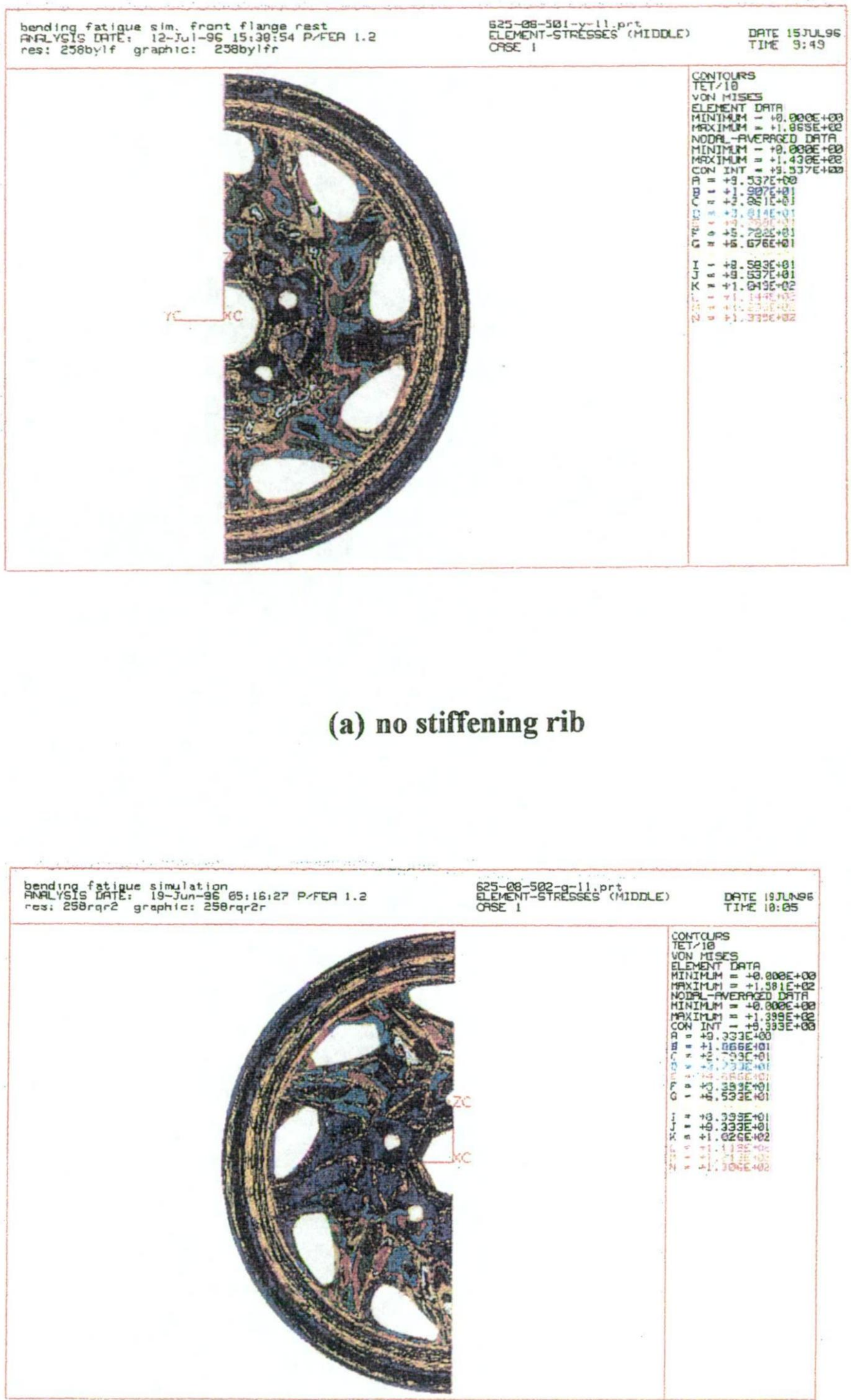


Fig 5.6 – Results of casting trial to demonstrate effect of feed channel.

It is common for all quality conscience company to pursue zero reject rate and although the above feed channel did not achieve this result it did produce a product that now met the normal expectations of a casting operation. The extra feed requirement was at the expense of weight and further improvements may not be possible given the customer weight restriction. The behaviour demonstrated above through figure 5.1 and 5.6 is repeated in a number of practical instances in the Southern Aluminium operating environment. This includes aluminium alloy wheels produced for Mazda and Nissan. Although the results above do not give a definitive answer it shows clearly the impact on product performance if the dimensional minimums are not taken into consideration. It is clear from the work performed that a dimension of 6 mm used for the feeding of a castings (as sown above) will result in a disastrous product (15% reject), whilst the employment of a minimum 8mm section minimum has a huge impact on the products performance (1.7% reject). For these reason it is clear that the use of less than 8 mm for the feed section of a low –pressure alloy wheel would be considered foolish.

The following 2 configurations are included to further demonstrate the use of FEA analysis to further verify the use of the methodology to demonstrate product performance. The results following in figure 5.7 (a) & (b) show the result of rotary FEA evaluation, and whilst the result demonstrates no significant difference it does demonstrate the ability of FEA to predict and be used for product optimisation.



(a) no stiffening rib

(b) with stiffening rib

Figure 5.7 – Rotary FEA result, hub restrained static loading

5.2 Concluding Remarks

It has been shown that the process of product optimisation to achieve minimum weight and good manufacturing ability within the low-pressure casting environment. The minimum material thickness required to meet all styling and manufacturing requirements, to this end a dimension of 6 mm has been used for non-feed areas of the wheel during low pressure die casting. For the feed areas of the low pressure casting, however, the dimension has to be greater than 6mm. The implications of the above decision are complemented by the qualitative analysis using finite element methods as discussed in the third chapter. This has been extensively tested over 500 aluminium alloy wheels for automobiles of Nissan, Ford, and Mazda. Although the defect rate decreased with increase in thickness, it is clear that an optimum value of thickness for the same operating condition exists which could range between 6mm-8mm.

In the example demonstrated above the appropriate corrective action was to make use of the rib to aid the requirements of feed and stress. The above analysis where all performed prior to the production of the final product and where critical to the understanding of how we are able to produce the product and finalise the design.

The Southern Aluminium experience has been that the above approach to minimising dimensions has enabled product to be delivered quickly and effectively minimising the time and expense in bringing the product to market in as cost effective manner as possible.

CHAPTER 6

FINAL CONCLUDING REMARKS AND FUTURE WORK

A brief introduction of manufacturing processes and a need for reliable quantitative information for effective casting is highlighted. The overall activities carried out in Southern Aluminium Pty. Ltd. a subsidiary of Comalco is discussed. The company's ability to produce high quality aluminium wheels and cater for the world automobile industry is discussed. It has been shown that there are four major manufacturing activities carried out on the aluminium alloy wheels in the plant namely: casting, heat treatment, machining and painting. While there are continual attempts to improve each of the four major manufacturing processes, casting as the first and indispensable process needed attention. There are various automobile companies such as Nissan, Ford and Mazda who are the regular customers of this plant and the varied designs, involving variety of thickness, have necessitated a better understanding of the casting process.

As a part of literature survey, a brief introduction of various casting processes is presented. The need for reliable quantitative parameters in low-pressure die-casting is highlighted to produce effective castings with a minimum thickness. Some models in the literature deal with two-dimensional models that are qualitative representations of this production process. It has been argued in the survey that the two dimensional analysis does not fully represent the practical case in industry. There are other attempts evident in the literature to understand the low-pressure die casting performance as a function of various process variables that highlight both qualitative and quantitative effects. The qualitative and quantitative trends covered are for various process variables giving a better understanding of the process.

An important aspect noted in the survey was that the information such as the behavior of minimum effective thickness in casting process has been a "classified information" for many industries. Many automobile manufacturers have treated such information as "trade secrets" not available to public research. Although much research in the literature highlighted the casting methods for aluminium alloys they have not considered the behaviour of these alloys as wheel castings involving various areas of cross sections. Hence the outcomes did not represent, from aluminum wheel manufacturers' point of view, a true behaviors of the alloy. Investigations involving simulation and modelling of the casting process using the state of the art packages are evident in the literature.

The finite element analysis as noted in the third chapter formed a very good basis for understanding the material behavior. This chapter highlighted that the reliability of quantitative trends, however, depended on the accuracy of magnitude of the loads applied at nodes. The finite element analysis is found to be applicable to the stress and strain analysis while the solidification rate is better analyzed using the finite difference methods. A commercially available software package, Magma is used to analyze both the cases. It should be noted that a brief description of the rationale and logic behind the software use is also presented. It has been found that the thin sections have a very high stress concentration, as expected, compared to the thin sections for the aluminum wheel under loading. Before identifying the minimum thickness a section can be cast, the procedure is verified using mechanical testing. A series of ultimate tensile strength, yield strength and elongation for the thin and thick sections using compressive testing machine have shown that the finite element analysis has reliable and comparable quantitative results. The other methods of finite element testing such as the stress analysis using rotary bending have complemented the mechanical tests carried out.

The Magma is further analyzed using a Plackett-Burman screening design of experiment (DOE). It has been found that the DOE is a scientific method of minimizing the amount of experiments required while maximizing the effect of variable examination of the experiment. This section also highlighted the need to carry out DOE and understanding the directional solidification, porosity and % solid in a wheel casting. Again using Magma finite difference package, these aspects have been well analyzed. Understanding of directional solidification has shown that the temperature distributions in the casting process are uniform. This also increases the credibility of the uniformity of the metal used. From porosity point of view it is quite normal for good thermal gradient wheels to exhibit a low porosity prediction which the Magma output has complemented. In studying the % solid, the cavity temperature clearly distinguished between the solidus and liquidus of 601 metal ie metal below 542°C will be solid and metal above 542°C will be liquid. This is a further substantiation of the normal behavior of 601 aluminum alloy.

While it is encouraging to see that the qualitative and quantitative trends are comparable to both the mechanical testing, finite element analysis and DOE using Plackett-Burman procedure, there is a further need to verify these trends using experiments.

A brief review of the flexible cell and its major constituents has been carried out, the casting part of the wheel manufacturing cycle is one of the highly sophisticated low-pressure die casting FMS cells in the country. A description of the flexible manufacturing system, the casting process both from an operational and a technical perspective has now been described. This Flexible manufacture system in combination with the tools provided sets various operating parameters, which in the using of the above flexible manufacturing system allows us to determine from a theoretical and a practical point of view the dimensional limits applied to the process. This set up described is used to investigate the dimensional limitations for low-pressure die-casting.

The final chapter described the nature of investigations and quantitative results achieved in casting minimum thickness sections for aluminium wheel castings. It has been shown that the process of product optimization to achieve minimum weight and good manufacturing ability within the low-pressure casting environment. The minimum material thickness required to meet all styling and manufacturing requirements, to this end a dimension of 6 mm has been used for non-feed areas of the wheel during low pressure die casting. For the feed areas of the low pressure casting, however, the dimension has to be greater than 6mm. The implications of the above decision are complemented by the qualitative analysis using finite element methods as discussed in the third chapter. This has been extensively tested over 500 aluminium alloy wheels for automobiles of Nissan, Ford, and Mazda. Although the defect rate decreased with increase in thickness, it is clear that an optimum value of thickness for the same operating condition exists should be 8mm, or if possible higher to achieve maximum possible yields.

In the example demonstrated above the appropriate corrective action was to make use of the rib to aid the requirements of feed and stress. The above analysis where all performed prior to the production of the final product and where critical to the understanding of how we are able to produce the product and finalise the design.

6.1 PROPOSED FUTURE WORK

There is a need to incorporate several other process variables such as the fill rate, temperatures, pressure variation, directional solidification, porosity and % solid to understand their combined effect on dimensional limitations. From an optimization point of view manufacturing models will need to be developed to incorporate process variables as inputs into the model to obtain the output of dimensional limitations. In other words a software can be developed, incorporating the logic and mathematics of optimization analysis, which when given the casting operating conditions outputs the achievable dimensional limitations. The part of the software can also accommodate various wheel designs working in conjunction with user friendly finite element software for preliminary qualitative trends.

REFERENCES

1. WORLD COMPETITIVE REPORT (1992), IMD and IMF foundation, Cologny/Geneva, Switzerland.

2. FROST, F. "A study of Heat-Treatment of Aluminium Castings" Masters thesis – University of Tasmania 1997

3. CAMPBELL, J. "Castings" Butterworth-Heinemann, 1991.

4. WOODWARD, R., "New Light Alloy Wheel Technology in Europe" Congress and Exposition, Cobo Hall, Detroit, February 26 – March 1979.

5. MOORE, H.D., KIBBEY, D.R. "Manufacturing : Materials and Processes", Third edition, Grid Publishing, Inc., Columbus, Ohio.

6. SOCIETY OF DIE CASTING ENGINEERS, "A comparison of high and Low pressure die casting" Society of die casting Engineers, October 1972.

7. "APQP Procedure", Internal quality/process documentation, SAPL, 1997.

8. FOUNDRY ARTICLE., "Moulding", Foundry Management and Technology, January 1997.

9. KREZIAK, G., RIGUAT C., SANTARINI, M., "Low pressure permanent mould process simulation of a thin wall aluminium casting", Materials science and Engineering, A173 (1993) , pp 255-259.

10. ALCOA, AURORA METALS, "The Fundamentals of permanent-mold", Precision metals, June 1997.

11. ROGERS, J.A., "Design and Developments in Aluminium Alloy Diecasting", Engineers Digest, March, 1981 Volume 42, No. 3.

12. OHTSUKA, Y., MIZUNO, K., YAMADA., "Application of Computer Simulation System to Aluminium Permanent Mold Castings" AFS Transactions, pp 635-645, 1989.

13. YOBARD, B., STEPHENSON, P. M., TODD J. D. W., "An expert system for Diagnosis of Aluminium Casting Defects" Foundry Trade Journal, 164, pp 837-838, 1990.

14. STEGEMAN, D., FETT. F., REIMCHE, W., "Use of real time microfocus radioscopy of light metal casting processes" Elsevier Science publishers B.V. , Amsterdam, 1989.

15. JACKNO, A., "Asea – Use of low pressure die casting", Society of Die casting Engineers, Conference paper, pp10-13, 1980.

16. CHIESA, F., "Heat losses during Filling of Permanent Moulds", Transactions of the Americans Foundryman's Society, Vol. 97, pp17-26, 1989.

17. ALUMASAC., "Use of Low pressure" Foundry Journal - Unknown.

18. APSLEY, S.D. et al, "Third report of working group P4: Dimensional tolerances in aluminium alloy gravity castings", British Foundryman, v 69 (3) , March 1976.

19. CORBET, C., "The Solstar Solidification-Simulation Software", The Foundryman, January 1992.

20. RODGERS, R., "Optimising the casting process", Foundry Management and Technology, September 1991.

21. CAMPBELL, J., "Solving problems in Foundry Methods Technology: Current Status of Computer Application", Conference report, 1990.

22. FUOCO, R., CORREA, E., CORREA, A.,CHIESA, F., "Typical defects in cast aluminium wheels", American Foundryman's Society, April 1997.

23. SMITH, R.L., PHENICIE, D.E., AGARWAL, A.K., KALLIEN, L.H., "Optimising the Production of a Die casting by numerical Simulation of Die Filling and Solidification", Die casting Engineer, V34(4), pp 40-48, 1993.

24. WHEELER, D.J., Understanding Industrial Experimentation", SPC Press, Knoxville, 1990.

25. SHNITKO, V., "Metal flow in dies during production of thin walled low-pressure diecastings" Liteinoe Proizvodsto, No. 11, pp 19-20, 1989.

26. FUNJINO, K., "Unique Forged Aluminium Wheel"., U-Mold Company Ltd., 1989.

27. GROOVER, H.P., ZIMMERS, E.W.,Jnr., "Computer- Aided Design and Manufacturers"., Prentice Hall, 1991.